I wish to preach not the doctrine of ignoble ease, but the doctrine of the strenuous life.

– Theodore Roosevelt

Innovation requires Austin, Texas. We need faster chips and great compilers. Both those things are from Austin.

– Guy Kawasaki
Course Topics

• Introduction

• Lexical Analysis: characters $\rightarrow$ words \textit{lexer}
  – Regular grammars
  – Hand-written lexical analyzer
  – Number conversion
  – Regular expressions
  – LEX

• Syntax Analysis: words $\rightarrow$ sentences \textit{parser}
  – Context-free grammars
  – Operator precedence
  – Recursive descent parsing
  – Shift-reduce parsing, YACC
  – Intermediate code
  – Symbol tables

• Code Generation
  – Code generation from trees
  – Register assignment
  – Array references
  – Subroutine calls

• Optimization
  – Constant folding, partial evaluation, Data flow analysis

• Object-oriented programming
program graph1(output); { Jensen & Wirth 4.9 }
const d = 0.0625; {1/16, 16 lines for [x,x+1]}
s = 32; {32 character widths for [y,y+1]}
h = 34; {character position of x-axis}
c = 6.28318; {2*pi} lim = 32;
var x,y : real; i,n : integer;
begin
  for i := 0 to lim do
    begin x := d*i; y := exp(-x)*sin(c*x);
      n := round(s*y) + h;
      repeat write(' '); n := n-1
        until n=0;
      writeln('*')
    end
end
end.
Introduction

• What a compiler does; why we need compilers
• Parts of a compiler and what they do
• Data flow between the parts
Machine Language

A computer is basically a very fast pocket calculator attached to a large memory. Machine instructions specify movement of data between the memory and calculator (ALU or Arithmetic/Logic Unit) or tell the ALU to perform operations.

Machine language is the only language directly executable on a computer, but it is very hard for humans to write:

- Absolute Addresses: hard to insert code.
- Numeric Codes, e.g. for operations: hard to remember.
- Bit fields, e.g. for registers: hard to pack into numeric form.
Assembly Language

Assembly Language is much easier to program in than Machine Language:

• Addresses are filled in by assembler: makes it easy to insert or remove code.

• Mnemonic codes for operations, e.g. ADD.

• Bit fields are handled by assembler.

However, it still is fairly difficult to use:

• One-to-one translation: one output instruction per source line.
  – Programmers write a fixed (small: 8 to 16) number of lines of code per day, independent of language.
  – A programmer costs $2 per minute, $1000 per day!

• Minimal error checking.
High-Level Language

- Higher-level language constructs:
  
  - Arithmetic Expressions: \( x := a + b \times c \)
  
  - Control Constructs:
    
    ```
    while expression do statement
    ```
  
  - Data Structures:
    
    ```
    people[i].spouse^.mother
    ```
  
  - Messages:
    
    ```
    obj.draw()
    ```

- One-to-many translation: one statement of input generates many machine instructions.

- Cost per machine instruction is much less than using assembly language.

- Error checking, e.g. detection of type errors. Compile-time errors are much cheaper to fix than runtime errors.
Compilers

A compiler translates language $X$ to language $Y$; “language” is understood very broadly:

- Compile a program to another program. High-level to machine language is the original definition of compiler.
- Compile a specification into a program.
- Compile a graph into a program.
- Translate one realization of an algorithm to another realization.
- Compile a program or specification to hardware.

---

2 This slide is by John Werth.
Sequential Phases of a Compiler\(^3\)

Input is a source program.

- Lexical analyzer: characters → words
- Syntax analyzer: words → sentences
  - Semantic analyzer
  - Intermediate code generator
- Code optimizer
- Code generator

We may think of this as an *analysis* process (understanding what the programmer wants to be done) followed by *synthesis* of a program that performs the intended computation.

These two modules are active throughout the compilation process:

- Symbol table manager
- Error handler

\(^3\)This slide adapted from one by John Werth.
Data Flow through the Compiler

Source Program
I/O
IF I > J THEN K := 0

Line Handler
Chars
IF I > J THEN K := 0

Lexical Analyzer

Tokens
Res Id Op Id Res Id Op Num
IF I > J THEN K := 0

Syntax Analyzer

IF
/ \
Trees > :=
/ \ / \ / \I J K 0

Code Generator
LDA I
CMP J

Code
BLE L17
LDAI 0
STA K

L17:
Line Handler

Below the level of the lexical analyzer will be low-level routines that perform input of the source file and get characters from it.

An input line will be treated as an array of characters, with a pointer to the next character (an index in the array).

Interfaces:

- **getchar()** Get the next character from the input line and move the pointer.

- **peekchar()** Get the next character from the input line without moving the pointer. (uses `ungetc()`)

- **peek2char()** Get the second character from the input line without moving the pointer.

The Line Handler will do such things as skipping whitespace (blanks, tabs, newlines), ignoring comments, handling continuation lines, etc. It may return special “end of statement” or “end of file” pseudo-characters.
Lexical Analyzer

The Lexical Analyzer (or Lexer) will convert characters into “words” or tokens, such as:

- Identifiers, e.g. `position`
- Reserved words or keywords, e.g. `begin`
- Numbers, e.g. `3.1415926e2`
- Operators, e.g. `>=`

The Lexical Analyzer may be called as a subroutine such as `gettoken()` to get the next token from the input string. It, in turn, calls the Line Handler routines.

The Lexical Analyzer returns a token data structure, consisting of:

- Token Type: identifier, reserved word, number, operator.
- Token Value:
  - Identifiers: string and symbol table pointer
  - Reserved words: integer code.
  - Numbers: internal binary form.
  - Operators: integer code.
The Syntactic Analyzer (or Parser) will analyze groups of related tokens ("words") that form larger constructs ("sentences") such as arithmetic expressions and statements:

- **while** *expression* **do** *statement* **;**
- **x := a + b * 7**

It will convert the *linear* string of tokens into *structured* representations such as expression trees and program flow graphs.
Semantic Analysis

This phase is concerned with the *semantics*, or meaning, of the program. Semantic processing is often performed along with syntactic analysis. It may include:

- Semantic error checking, such as checking for type errors.
- Insertion of extra operations, such as *type coercion* or code for array references.
Lexical Analysis

If speed is needed, the Line Handler and Lexical Analyzer can be coded in assembly language.

The Lexical Analyzer does the following:

- Reads input characters.
- Groups characters into meaningful units or “words”, producing data structures called tokens.
- Converts units to internal form, e.g. converts numbers to machine binary form.
- Serves as a front end for and provides input to the Parser.
## Character Codes: ASCII

<table>
<thead>
<tr>
<th>Dec</th>
<th>Char</th>
<th>Dec</th>
<th>Char</th>
<th>Dec</th>
<th>Char</th>
<th>Dec</th>
<th>Char</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>NUL (null)</td>
<td>32</td>
<td>SPACE</td>
<td>64</td>
<td>@</td>
<td>96</td>
<td>‘</td>
</tr>
<tr>
<td>1</td>
<td>SOH (start of heading)</td>
<td>33</td>
<td>!</td>
<td>65</td>
<td>A</td>
<td>97</td>
<td>a</td>
</tr>
<tr>
<td>2</td>
<td>STX (start of text)</td>
<td>34</td>
<td>&quot;</td>
<td>66</td>
<td>B</td>
<td>98</td>
<td>b</td>
</tr>
<tr>
<td>3</td>
<td>ETX (end of text)</td>
<td>35</td>
<td>#</td>
<td>67</td>
<td>C</td>
<td>99</td>
<td>c</td>
</tr>
<tr>
<td>4</td>
<td>EOT (end of transmission)</td>
<td>36</td>
<td>$</td>
<td>68</td>
<td>D</td>
<td>100</td>
<td>d</td>
</tr>
<tr>
<td>5</td>
<td>ENQ (enquiry)</td>
<td>37</td>
<td>%</td>
<td>69</td>
<td>E</td>
<td>101</td>
<td>e</td>
</tr>
<tr>
<td>6</td>
<td>ACK (acknowledge)</td>
<td>38</td>
<td>&amp;</td>
<td>70</td>
<td>F</td>
<td>102</td>
<td>f</td>
</tr>
<tr>
<td>7</td>
<td>BEL (bell)</td>
<td>39</td>
<td>'</td>
<td>71</td>
<td>G</td>
<td>103</td>
<td>g</td>
</tr>
<tr>
<td>8</td>
<td>BS (backspace)</td>
<td>40</td>
<td>(</td>
<td>72</td>
<td>H</td>
<td>104</td>
<td>h</td>
</tr>
<tr>
<td>9</td>
<td>TAB (horizontal tab)</td>
<td>41</td>
<td>)</td>
<td>73</td>
<td>I</td>
<td>105</td>
<td>i</td>
</tr>
<tr>
<td>10</td>
<td>LF (line feed, new line)</td>
<td>42</td>
<td>*</td>
<td>74</td>
<td>J</td>
<td>106</td>
<td>j</td>
</tr>
<tr>
<td>11</td>
<td>VT (vertical tab)</td>
<td>43</td>
<td>+</td>
<td>75</td>
<td>K</td>
<td>107</td>
<td>k</td>
</tr>
<tr>
<td>12</td>
<td>FF (form feed, new page)</td>
<td>44</td>
<td>,</td>
<td>76</td>
<td>L</td>
<td>108</td>
<td>l</td>
</tr>
<tr>
<td>13</td>
<td>CR (carriage return)</td>
<td>45</td>
<td>-</td>
<td>77</td>
<td>M</td>
<td>109</td>
<td>m</td>
</tr>
<tr>
<td>14</td>
<td>SO (shift out)</td>
<td>46</td>
<td>.</td>
<td>78</td>
<td>N</td>
<td>110</td>
<td>n</td>
</tr>
<tr>
<td>15</td>
<td>SI (shift in)</td>
<td>47</td>
<td>/</td>
<td>79</td>
<td>O</td>
<td>111</td>
<td>o</td>
</tr>
<tr>
<td>16</td>
<td>DLE (data link escape)</td>
<td>48</td>
<td>0</td>
<td>80</td>
<td>P</td>
<td>112</td>
<td>p</td>
</tr>
<tr>
<td>17</td>
<td>DC1 (device control 1)</td>
<td>49</td>
<td>1</td>
<td>81</td>
<td>Q</td>
<td>113</td>
<td>q</td>
</tr>
<tr>
<td>18</td>
<td>DC2 (device control 2)</td>
<td>50</td>
<td>2</td>
<td>82</td>
<td>R</td>
<td>114</td>
<td>r</td>
</tr>
<tr>
<td>19</td>
<td>DC3 (device control 3)</td>
<td>51</td>
<td>3</td>
<td>83</td>
<td>S</td>
<td>115</td>
<td>s</td>
</tr>
<tr>
<td>20</td>
<td>DC4 (device control 4)</td>
<td>52</td>
<td>4</td>
<td>84</td>
<td>T</td>
<td>116</td>
<td>t</td>
</tr>
<tr>
<td>21</td>
<td>NAK (negative acknowledge)</td>
<td>53</td>
<td>5</td>
<td>85</td>
<td>U</td>
<td>117</td>
<td>u</td>
</tr>
<tr>
<td>22</td>
<td>SYN (synchronous idle)</td>
<td>54</td>
<td>6</td>
<td>86</td>
<td>V</td>
<td>118</td>
<td>v</td>
</tr>
<tr>
<td>23</td>
<td>ETB (end of trans. block)</td>
<td>55</td>
<td>7</td>
<td>87</td>
<td>W</td>
<td>119</td>
<td>w</td>
</tr>
<tr>
<td>24</td>
<td>CAN (cancel)</td>
<td>56</td>
<td>8</td>
<td>88</td>
<td>X</td>
<td>120</td>
<td>x</td>
</tr>
<tr>
<td>25</td>
<td>EM (end of medium)</td>
<td>57</td>
<td>9</td>
<td>89</td>
<td>Y</td>
<td>121</td>
<td>y</td>
</tr>
<tr>
<td>26</td>
<td>SUB (substitute)</td>
<td>58</td>
<td>:</td>
<td>90</td>
<td>Z</td>
<td>122</td>
<td>z</td>
</tr>
<tr>
<td>27</td>
<td>ESC (escape)</td>
<td>59</td>
<td>;</td>
<td>91</td>
<td>[</td>
<td>123</td>
<td>{</td>
</tr>
<tr>
<td>28</td>
<td>FS (file separator)</td>
<td>60</td>
<td>&lt;</td>
<td>92</td>
<td>\</td>
<td>124</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>GS (group separator)</td>
<td>61</td>
<td>=</td>
<td>93</td>
<td>]</td>
<td>125</td>
<td>}</td>
</tr>
<tr>
<td>30</td>
<td>RS (record separator)</td>
<td>62</td>
<td>&gt;</td>
<td>94</td>
<td>^</td>
<td>126</td>
<td>~</td>
</tr>
<tr>
<td>31</td>
<td>US (unit separator)</td>
<td>63</td>
<td>?</td>
<td>95</td>
<td>_</td>
<td>127</td>
<td>DEL</td>
</tr>
</tbody>
</table>
Character Classes

At the lowest level of grammar, there is a need to classify characters into classes. This can be done by lookup in an array indexed by the character code. Typical classes include:

- Numerals: 0 1 2 3 4 5 6 7 8 9
- Alphabetic: A B C . . . Z
- Whitespace: blank, tab, newline.
- Special: ( ) [ ] + = . etc.
- Other: characters not in the language ~ @ #

<table>
<thead>
<tr>
<th>Char</th>
<th>ASCII</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>60₈</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>61₈</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>101₈</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>102₈</td>
<td>1</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Implementation of Character Classes

Character class names are defined as small-integer constants. A character class array is initialized to map from a character code to the appropriate class.

```
#define ALPHA 1 /* char class names */
#define NUMERIC 2
#define SPECIAL 3

int CHARCLASS[256]; /* char class array */

char specchar[] = "+-*/:=<>^.,;()[]{}";

for (i = 'a'; i <= 'z'; ++i) /* init */
    CHARCLASS[i] = ALPHA;
for (i = '0'; i <= '9'; ++i)
    CHARCLASS[i] = NUMERIC;
for (i = 0 ; specchar[i] != \0 ; ++i)
    CHARCLASS[specchar[i]] = SPECIAL;
```

The class of a character is looked up in the array:

```
c = peekchar();
if (CHARCLASS[c] == ALPHA) ...
```
A lexical analyzer can easily be written by hand. Typically, such a program will call functions `getchar()` and `peekchar()` to get characters from the input.

The lexical analyzer is likewise called as a function, with an entry such as `gettoken()`. The program is structured as:

1. A “big switch” that skips white space, peeks at the next character to guess what kind of token will be next, and calls the appropriate routine.

2. A set of routines to get particular kinds of tokens, such as identifiers, numbers, strings, or operators.

Typically, a routine will process all tokens that look alike, *e.g.*, all kinds of numbers, or both identifiers and reserved words.
Example Lexical Analyzer

/* The 'big switch': guess token type, call a routine to parse it */
TOKEN gettoken()
{
    TOKEN tok; int c, cclass;
    tok = tallocl(); /* allocate new token */
    skipblanks(); /* and comments */
    if ((c = peekchar()) != EOF)
    {
        cclass = CHARCLASS[c];
        if (cclass == ALPHA)
            identifier(tok);
        else if (cclass == NUMERIC)
            number(tok);
        else if (c == '\')
            getstring(tok);
        else special(tok);
    }
    else EOFLGLG = 1;
    return(tok);
}
static char *reserved[] = { "array", "begin", ... };
Lexical Language Design

A language designer should avoid ambiguity in the design of the lexical syntax of a language.

1. *Reserved words* are a good idea to avoid ambiguity between user symbols and language command words.

   DO 10 I = 1,25
   DO 10 I = 1.25
   FORMAT(I5)
   FORMAT(I5) = 1.2

   There should not be too many reserved words.

2. Don’t allow spaces inside tokens. Space, or nothing, should never be an operator.

3. Different kinds of tokens should look different at the left end (initial character).

4. Avoid ambiguous combinations of tokens that would require long look-ahead.

5. Avoid “noise” such as ugly special characters. These require extra keystrokes and make programs hard to read. %rax

6. Are upper- and lower-case letters equivalent?
Token Data Structure

Converting lexical items into tokens simplifies later processing by reducing the input to a few standard kinds of tokens: reserved words, identifiers, numbers, operators, strings, delimiters. The tokens serve as the terminal symbols of the parser grammar.

A token will contain:

1. token type (identifier, operator, etc.)
2. data type: a numeric code indicating integer, real, etc.
3. pointers to the symbol table
4. pointers for making trees from tokens
5. value of the token (identifier name, number value, numeric code indicating which operator).
Example Token Data Structure

typedef struct tokn {
    int  tokentype; /* OPERATOR, etc */
    int  basicdt;   /* INTEGER, REAL, etc */
    struct symtbr * symtype;
    struct symtbr * symentry;
    struct tokn *operands;
    struct tokn *link;
    union { char  tokenstring[16];
            int    which;
            long   intnum;
            float  realnum; } tokenval;
} TOKENREC, *TOKEN;

symtype     pointer to type in symbol table
symentry    pointer to variable in symbol table
operands    down pointer to operand tokens
link        side pointer to sibling token
whichval    integer code: which operator, etc.
            defined as tokenval.whic
stringval   string constant or variable name
intval      value of integer constant
realval     value of real constant
Number Conversion

Arabic (Indian) numerals are written in the form $a_na_{n-1}...a_1a_0$ denoting, in number base $r$, the integer:

$$a_n \cdot r^n + a_{n-1} \cdot r^{n-1} + ... + a_1 \cdot r^1 + a_0$$

Factoring this expression yields:

$$((...((0 \cdot r + a_n) \cdot r + a_{n-1}) \cdot r + ...) \cdot r + a_1) \cdot r + a_0$$

This suggests an algorithm for converting a number expressed by digits $d_nd_{n-1}...d_1d_0$ to internal form in a left-to-right scan:

1. Initialize the accumulator, $\text{num} = 0$.
2. For each new digit, $d_i$, let $a$ be the number denoted by $d_i$:
   - In C, $(d_i - '0')$
   - In Lisp, `(- (char-code d_i) (char-code \#\0))`
   Then set $\text{num} = \text{num} \times r + a$.
3. After all digits have been processed, $\text{num}$ is the numeric value in internal form.
Simple Number Scanner

```c
void number (TOKEN tok)
{
    long num;
    int c, charval;
    num = 0;
    while ( (c = peekchar()) != EOF
        && CHARCLASS[c] == NUMERIC)
    {
        c = getchar();
        charval = (c - '0');
        num = num * 10 + charval;
    }
    tok->tokentype = NUMBERTOK;
    tok->basicdt = INTEGER;
    tok->intval = num;
}
```
Lexical Analyzer Output

Started scanner test.

tokentype:  2 which:  19           program

tokentype:  3 value:             graph1

tokentype:  1 which:  4          (

tokentype:  3 value:             output


tokentype:  1 which:  5          )

tokentype:  1 which:  2          ;

tokentype:  2 which:  4          const

tokentype:  3 value:             d

tokentype:  0 which:  6          =

tokentype:  5 type:  1 6.250000e-02

tokentype:  1 which:  2          ;

tokentype:  3 value:             s

tokentype:  0 which:  6          =

tokentype:  5 type:  0 32

tokentype:  1 which:  2          ;

tokentype:  3 value:             h

tokentype:  0 which:  6          =

tokentype:  5 type:  0 34

tokentype:  1 which:  2          ;

tokentype:  3 value:             c

tokentype:  0 which:  6          =

tokentype:  5 type:  1 6.283180e+00

tokentype:  1 which:  2          ;
Floating Point Numbers

Numbers containing a decimal point can be converted in a manner similar to that used for integers.

The important thing to note is that the decimal point is only a place marker to denote the boundary between the integer and fraction parts.

1. Convert the number to an integer as if the decimal point were not present.
2. Count the number of digits after the decimal point has been found.
3. Include only an appropriate number of significant digits in the mantissa accumulation.
4. Leading zeros are not significant, but must be counted if they follow the decimal point.
5. At the end:
   (a) Float the accumulated mantissa
   (b) Combine the digit counts and the specified exponent, if any.
   (c) Multiply or divide the number by the appropriate power of 10 (from a table).
IEEE Floating Point Standard

The exponent in all three binary formats is an unsigned binary integer with an implied bias added to it. The bias values for single, double, and extended precision are 127, 1023, and 16383, respectively. When the bias is subtracted from the value of the exponent, the result represents a signed, two's complement power of two which, when multiplied by the mantissa, yields the magnitude of a normalized floating-point number. Note that the use of biased exponents allows floating-point numbers in memory to be compared using the M68000 Family integer compare instruction (CMP), regardless of the absolute magnitude of the exponents.

Data formats for single and double precision numbers differ slightly from the data format for extended precision numbers in the representation of the mantissa. A normalized mantissa, for all three precisions, is always in the range [1.0...2.0). The extended precision data format explicitly represents the entire mantissa, including the explicit integer part bit. However, for single and double precision data formats, only the fractional portion of the mantissa is explicitly represented and the integer part is always one. Thus, the integer part bit is implicit for single and double precision formats.

The IEEE standard has created the term "significand" to bridge this difference and to avoid the historical implications of the term mantissa. The IEEE standard defines a significand as that component of a binary floating-point number which consists of an explicit or implicit leading bit to the left of the implied binary point and a fraction field to the right of the implied binary point.

This manual uses the terms mantissa and significand interchangeably, given the relationships as shown below.

- Single Precision Mantissa = Single Precision Significand
- Single Precision Mantissa = 1.<23-Bit Fraction Field>
- Double Precision Mantissa = Double Precision Significand
- Double Precision Mantissa = 1.<52-Bit Fraction Field>
Floating Point Examples

/* floats.exmp  Print out floating point numbers  06 Feb 91 */
static float nums[30] = { 0.0, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0,
  9.0, 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, 16.0, 17.0, 3.1, 3.14,
  3.1415927, 0.5, 0.25, 0.125, -1.0, -2.0, -3.0, -0.5, -0.25, -3.1415927 };

printnum(f,plainf)
  float f; unsigned plainf;  /* look at the float as a bit string */
  { int sign, exp, expb;  long mant, mantb;
  { sign = (plainf >> 31) & 1;
    exp = (plainf >> 20) & 2047;
    expb = exp - 1023;
    mant = plainf & 1048575;
    mantb = mant + 1048576;
    printf("%12f %11o %1o %4o %5d %7o %7o\n",
         f, plainf, sign, exp, expb, mant, mantb); } }

/* This appears to be double-precision floating point format: */
/* 1 bit sign, 11 bits biased exponent, 20 bits mantissa + 32 in next word */

<table>
<thead>
<tr>
<th>floating</th>
<th>octal</th>
<th>sign</th>
<th>biased exponent</th>
<th>corrected exponent</th>
<th>actual mantissa</th>
<th>corrected mantissa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000000</td>
<td>00000000</td>
<td>0</td>
<td>0</td>
<td>-1023</td>
<td>0</td>
<td>4000000</td>
</tr>
<tr>
<td>1.000000</td>
<td>7774000000</td>
<td>0</td>
<td>1777</td>
<td>0</td>
<td>0</td>
<td>4000000</td>
</tr>
<tr>
<td>2.000000</td>
<td>10000000000</td>
<td>0</td>
<td>2000</td>
<td>1</td>
<td>0</td>
<td>4000000</td>
</tr>
<tr>
<td>3.000000</td>
<td>10002000000</td>
<td>0</td>
<td>2000</td>
<td>1</td>
<td>2000000</td>
<td>6000000</td>
</tr>
<tr>
<td>4.000000</td>
<td>10004000000</td>
<td>0</td>
<td>2001</td>
<td>2</td>
<td>0</td>
<td>4000000</td>
</tr>
<tr>
<td>5.000000</td>
<td>10005000000</td>
<td>0</td>
<td>2001</td>
<td>2</td>
<td>1000000</td>
<td>5000000</td>
</tr>
<tr>
<td>9.000000</td>
<td>10010400000</td>
<td>0</td>
<td>2002</td>
<td>3</td>
<td>4000000</td>
<td>4400000</td>
</tr>
<tr>
<td>3.100000</td>
<td>10002146314</td>
<td>0</td>
<td>2000</td>
<td>1</td>
<td>2146314</td>
<td>6146314</td>
</tr>
<tr>
<td>3.140000</td>
<td>10002217270</td>
<td>0</td>
<td>2000</td>
<td>1</td>
<td>2217270</td>
<td>6217270</td>
</tr>
<tr>
<td>3.141593</td>
<td>10002220773</td>
<td>0</td>
<td>2000</td>
<td>1</td>
<td>2220773</td>
<td>6220773</td>
</tr>
<tr>
<td>0.500000</td>
<td>77700000000</td>
<td>0</td>
<td>1776</td>
<td>-1</td>
<td>0</td>
<td>4000000</td>
</tr>
<tr>
<td>0.250000</td>
<td>77640000000</td>
<td>0</td>
<td>1775</td>
<td>-2</td>
<td>0</td>
<td>4000000</td>
</tr>
<tr>
<td>0.125000</td>
<td>77600000000</td>
<td>0</td>
<td>1774</td>
<td>-3</td>
<td>0</td>
<td>4000000</td>
</tr>
<tr>
<td>-1.000000</td>
<td>27774000000</td>
<td>1</td>
<td>1777</td>
<td>0</td>
<td>0</td>
<td>4000000</td>
</tr>
<tr>
<td>-2.000000</td>
<td>30000000000</td>
<td>1</td>
<td>2000</td>
<td>1</td>
<td>0</td>
<td>4000000</td>
</tr>
<tr>
<td>-3.000000</td>
<td>30002000000</td>
<td>1</td>
<td>2000</td>
<td>1</td>
<td>2000000</td>
<td>6000000</td>
</tr>
<tr>
<td>-0.500000</td>
<td>27770000000</td>
<td>1</td>
<td>1776</td>
<td>-1</td>
<td>0</td>
<td>4000000</td>
</tr>
<tr>
<td>-3.141593</td>
<td>30002220773</td>
<td>1</td>
<td>2000</td>
<td>1</td>
<td>2220773</td>
<td>6220773</td>
</tr>
</tbody>
</table>
Errors

Several kinds of errors are possible:

- Lexical: $x := y \sim z$
  The character $\sim$ is not allowed in Pascal.

- Syntactic: $x := y \ z$
  There is no operator between $y$ and $z$.

- Semantic: $x := y \ mod \ 3.14$
  The operator $\text{mod}$ requires integer arguments.

The seriousness of errors can vary:

- Diagnostic: not necessarily an error, but might be:
  $x == 3.14$ may not be a meaningful comparison.

- Error: definitely an error; code generation will be aborted, but compilation may continue.

- Fatal error: so bad that the compiler must stop immediately.

*Cascading errors* occur when one real error causes many reported errors, e.g. forgetting to declare a variable can cause an error at each use.

---

4This slide adapted from one by John Werth.
Error Messages

The compiler writer has a serious obligation: the compiler must produce either correct output code or an error message.

Good error messages can save a great deal of programmer time; this makes it worth the trouble to produce them.

1. The message should be written out as text.
2. A pointer to the point of the error in the input program should be provided when appropriate.
3. Values from the program should be included in the message where appropriate.
4. Diagnostic messages (e.g., unused variables) should be included, but user should be able to turn them off.

\[ X[CVAR] := 3.14 \]

↑

*ERROR* CVAR, of type COMPLEX, may not be used as a subscript.
Formal Syntax

There is a great deal of mathematical theory concerning the syntax of languages. This theory is based on the work of Chomsky.

Formal syntax is better at describing artificial languages such as programming languages than at describing natural languages.
A grammar specifies the legal syntax of a language. The kind of grammar most commonly used in computer language processing is a context-free grammar. A grammar specifies a set of productions; non-terminal symbols (phrase names or parts of speech) are enclosed in angle brackets. Each production specifies how a nonterminal symbol may be replaced by a string of terminal or nonterminal symbols, e.g., a Sentence is composed of a Noun Phrase followed by a Verb Phrase.

\[
<\text{S}> \rightarrow <\text{NP}> <\text{VP}>
\]

\[
<\text{NP}> \rightarrow <\text{ART}> <\text{ADJ}> <\text{NOUN}>
\]

\[
<\text{NP}> \rightarrow <\text{ART}> <\text{NOUN}>
\]

\[
<\text{NP}> \rightarrow <\text{ART}> <\text{NOUN}> <\text{PP}>
\]

\[
<\text{VP}> \rightarrow <\text{VERB}> <\text{NP}>
\]

\[
<\text{VP}> \rightarrow <\text{VERB}> <\text{NP}> <\text{PP}>
\]

\[
<\text{PP}> \rightarrow <\text{PREP}> <\text{NP}>
\]

\[
<\text{ART}> \rightarrow \text{A} | \text{AN} | \text{THE}
\]

\[
<\text{NOUN}> \rightarrow \text{BOY} | \text{DOG} | \text{LEG} | \text{PORCH}
\]

\[
<\text{ADJ}> \rightarrow \text{BIG}
\]

\[
<\text{VERB}> \rightarrow \text{BIT}
\]

\[
<\text{PREP}> \rightarrow \text{ON}
\]
Language Generation

Sentences can be generated from a grammar by the following procedure:

• Start with the sentence symbol, $<S>$.

• Repeat until no nonterminal symbols remain:
  – Choose a nonterminal symbol in the current string.
  – Choose a production that begins with that nonterminal.
  – Replace the nonterminal by the right-hand side of the production.

$<S>$
$<NP> <VP>$
$<ART> <NOUN> <VP>$
THE $<NOUN> <VP>$
THE DOG $<VP>$
THE DOG $<VERB> <NP>$
THE DOG $<VERB> <ART> <NOUN>$
THE DOG $<VERB> THE <NOUN>$
THE DOG BIT THE $<NOUN>$
THE DOG BIT THE BOY
Parsing

Parsing is the inverse of generation: the assignment of structure to a linear string of words according to a grammar; this is much like the “diagramming” of a sentence taught in grammar school.

Parts of the parse tree can then be related to object symbols in the computer’s memory.
Ambiguity

Unfortunately, there may be many ways to assign structure to a sentence (e.g., what does a PP modify?):
Notation

The following notations are used in describing grammars and languages:

\( V^* \)  
Kleene closure: a string of 0 or more elements from the set \( V \).

\( V^+ \)  
1 or more elements from \( V \)

\( V^? \)  
0 or 1 elements from \( V \) (i.e., optional)

\( a|b \)  
either \( a \) or \( b \)

\(< nt >\)  
a nonterminal symbol or phrase name

\( \epsilon \)  
the empty string
Phrase Structure Grammar

A grammar describes the structure of the sentences of a language in terms of components, or phrases. The mathematical description of phrase structure grammars is due to Chomsky.\(^5\)

Formally, a Grammar is a four-tuple \(G = (T, N, S, P)\) where:

- **T** is the set of *terminal symbols* or *words* of the language.
- **N** is a set of *nonterminal symbols* or *phrase names* that are used in specifying the grammar. We say \(V = T \cup N\) is the *vocabulary* of the grammar.
- **S** is a distinguished element of \(N\) called the *start symbol*.
- **P** is a set of *productions*, \(P \subseteq V^*NV^* \times V^*\). We write productions in the form \(a \rightarrow b\) where \(a\) is a string of symbols from \(V\) containing at least one nonterminal and \(b\) is any string of symbols from \(V\).

---

Chomsky defined 4 classes of languages, each of which is a proper superset of the rest:

Type 0: General Phrase-structure
Type 1: Context Sensitive
Type 2: Context Free
Type 3: Regular

These languages can be characterized in several ways:

- Type of allowable productions in the grammar
- Type of recognizing automaton
- Memory required for recognition
Recognizing Automaton

A recognizing automaton is an abstract computer that reads symbols from an input tape. It has a finite control (computer program) and an auxiliary memory.

The recognizer answers “Yes” or “No” to the question “Is the input string a member of the language?”

The kinds of languages that can be recognized depend on the amount of auxiliary memory the automaton has (finite, pushdown stack, tape whose size is a linear multiple of input length, infinite tape).
# Chomsky Language Hierarchy

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Allowable Productions</th>
<th>Example Language</th>
<th>Example Grammar</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Type 0</td>
<td>Unrestricted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Context Sensitive</td>
<td>[\alpha \rightarrow \beta] where (</td>
<td>\alpha</td>
<td>\leq</td>
</tr>
<tr>
<td>2</td>
<td>Context Free</td>
<td>[A \rightarrow \alpha] [A \in N] [\alpha \in V^*]</td>
<td>[^{a^n}b^n]</td>
<td>[S \rightarrow aSb] [S \rightarrow ab]</td>
</tr>
<tr>
<td>3</td>
<td>Regular Right Linear Finite Automaton Recognizable</td>
<td>[A \rightarrow xB] [A \rightarrow x] [A, B \in N] [x \in T^*]</td>
<td>[^{a^n}b]</td>
<td>[S \rightarrow ab] [S \rightarrow aS]</td>
</tr>
</tbody>
</table>
Regular Languages

**Productions:**  
\[ A \rightarrow xB \]  
\[ A \rightarrow x \]  
\[ A, B \in N \]  
\[ x \in T^* \]

- Only *one* nonterminal can appear in any derived string, and it must appear at the right end.
- Equivalent to a *deterministic finite automaton* (simple program).
- Parser never has to back up or do search.
- Linear parsing time.
- Used for simplest items (identifiers, numbers, word forms).
- Any *finite* language is regular.
- Any language that can be recognized using finite memory is regular.
Example Regular Language

A binary integer can be specified by a regular grammar:

\[ < S > \rightarrow 0 < S > \]
\[ < S > \rightarrow 1 < S > \]
\[ < S > \rightarrow 0 \]
\[ < S > \rightarrow 1 \]

The following is a parse tree for the string \texttt{110101}. Note that the tree is linear in form; this is the case for any regular language.
**lex**

**lex** is a lexical analyzer generator, part of a compiler-compiler system when paired with **yacc**.\(^6\)

**lex** allows a lexical analyzer to be constructed more easily than writing one by hand. **lex** allows the grammar to be specified using *regular expressions*; these are converted to a nondeterministic finite automaton (NFA), which is converted to a deterministic finite automaton (DFA), which is converted to tables to control a table-driven parser.

**lex** reads a source file, named using a `.l` suffix, compiles it, and produces an output file that is always called `lex.yy.c`. This is a C file that can be compiled using the C compiler to produce an executable.

---

\(^6\)There are Gnu versions of **lex** and **yacc** called **flex** and **bison**. These are mostly, but not completely, compatible with **lex** and **yacc**.
Regular Expressions

Regular expressions are a more convenient way (than a regular grammar) to specify a regular language. We will use lex conventions for specifying regular expressions. An expression is specified in left-to-right order.

Expression: Meaning:

[ chars ] Any member of the set of characters chars.
[ c₁ - c₂ ] Any character from c₁ through c₂.
[^ chars ] Any character except chars.
( specs ) Used to group specifications specs.
{ category } An instance of a previously named category.
" string " Exactly the specified string.
s₁ | s₂ s₁ or s₂
spec * Zero or more repetitions of spec.
spec + One or more repetitions of spec.
spec ? Optional spec.
spec { m, n} m through n repetitions of spec.
Lex Specifications

iclaring definitions
%
translatio rules
%
auxiary procedures

• declarations: include and manifest constants (identifier declared to represent a constant).

• regular definitions: definition of named syntactic constructs such as letter using regular expressions.

• translation rules: pattern / action pairs

• auxiliary procedures: arbitrary C functions copied directly into the generated lexical analyzer.

\[\text{\textsuperscript{7}}\text{slide by John Werth.}\]
Sample lex Specification

 televised version of Fig. 3.23 from Aho, Lam, Sethi, and Ullman, Compilers.

```c
#define LT 8  /* Example of use: */
#define LE 9  /* lex /projects/cs375/lexasu.l compile lexasu.l to C */
#define EQ 6  /* cc lex.yy.c -lI Compile lex output with C */
#define NE 7  /* a.out Execute C output */
#define GT 11 /* if switch then 3.14 else 4 Test data */
#define GE 10 /* D Control-D for EOF to stop */
#define ID 3
#define NUMBER 5
#define OP 1 /* to avoid returning 0 */
#define IF 13
#define THEN 23
#define ELSE 7
int yylval; /* type of the returned value */

{ /* regular definitions */

  delim [ \t\n]
  ws  {delim}+
  letter [A-Za-z]
  digit [0-9]
  id  {letter}({letter}|{digit})*
  number {digit}+(\.{digit}+)?(E[+\-]?{digit}+)?

  \%

  {ws}  { /* no action and no return */ }
  if   { return(IF); }
  then { return(THEN); }
  else { return(ELSE); }
  {id} { yylval = install_id(); return(ID); }
  {number} { yylval = install_num(); return(NUMBER); }
  "<"  { yylval = LT; return(OP); }
  "<=" { yylval = LE; return(OP); }
  "="  { yylval = EQ; return(OP); }
  ">"  { yylval = NE; return(OP); }
  ">=" { yylval = GE; return(OP); }

8Runnable version of Fig. 3.23 from Aho, Lam, Sethi, and Ullman, Compilers.
```
%% /* C functions */

install_id() { printf("id %10s n = %4d\n", yytext, yyleng); }

install_num() { printf("num %10s n = %4d\n", yytext, yyleng); }

yywrap() { return(1); } /* lex seems to need this. */

void main() /* Call yylex repeatedly to test */
{ int res, done;
  done = 0;
  while (done == 0)
    { res = yylex();
      if (res != 0)
      { 
        printf("yylex result = %4d\n", res);
      }
      else done = 1;
    }
  exit(0);
}
The file `lex.yy.c` produced by `lex` has the following structure (different versions of `lex` may put the sections in different orders).

<table>
<thead>
<tr>
<th>User declarations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code derived from user actions</td>
</tr>
<tr>
<td>User’s C code</td>
</tr>
<tr>
<td>Parsing Table from user’s grammar</td>
</tr>
<tr>
<td>“Canned” Parser in C</td>
</tr>
</tbody>
</table>
Comments on Sample lex

Manifest Constants: these definitions are surrounded by %{ ... %} and will be copied verbatim into the generated program.

Regular Definitions: these are names followed by a regular expression. For example, delim is one of the characters blank, tab, or newline.

Note that if a string is a name then it is surrounded by braces (as delim is in the definition of ws) so that it will not be interpreted as a set of characters.

[A–Z] is the set of characters from A to Z.

Parentheses are meta-symbols used to group. | is a meta-symbol for union. ? is a meta-symbol for 0 or more occurrences. – is a meta-symbol for range.

\ is an escape which allows a meta-symbol to be used as a normal character. "" has the same effect.

---

9slide by John Werth.
Translation Section

The {ws} rule causes the lexical analyzer to skip all delimiters until the next non-delimiter.

The if rule recognizes the string ’if’. When it is found the lexical analyzer returns the token IF, a manifest constant.

The {id} rule must do three jobs:

1. record the id in the symbol table
2. return a pointer to the specific id
3. return the token ID to signify that an id was seen

The first two are accomplished by

\[ \text{yyllval} = \text{install}(id); \]

\text{yyllval} is a global used for this purpose in Yacc. The third is accomplished by \text{return(ID)};

The action for {number} is similar.

The rules for the relational operators set \text{yyllval} to specific manifest constants to show which value was found and return the token RELOP to signify that a relational operator was seen.

\footnote{slide by John Werth.}
Lex Conventions\textsuperscript{11}

• The program generated by Lex matches the longest possible prefix of the input. For example, if $<=$ appears in the input then rather than matching only the $<$ (which is also a legal pattern) the entire string is matched.

• Lex keywords are:
  – \texttt{yylval}: value returned by the lexical analyzer (pointer to token)
  – \texttt{yytext}: pointer to lexeme (array of characters that matched the pattern)
  – \texttt{yyleng}: length of the lexeme (number of chars in \texttt{yytext}).

• If two rules match a prefix of the same and greatest length then the first rule appearing (sequentially) in the translation section takes precedence.
  For example, \texttt{if} is matched by both \texttt{if} and \{\texttt{id}\}. Since the \texttt{if} rule comes first, that is the match that is used.

\textsuperscript{11}slide by John Werth.
The Lookahead Operator

If $r_1$ and $r_2$ are patterns, then $r_1/r_2$ means match $r_1$ only if it is followed by $r_2$.

For example, Fortran has a **DO** statement, similar to the **for** statement; unfortunately, the **DO** statement could look very similar to an assignment statement:

\[
\text{DO 10 I = 1,25 } \quad \text{cf. for (i=1; i<=25; i++)}
\]

\[
\text{DO 10 I = 1.25 } \quad \text{do10i = 1.25;}
\]

\[
\text{DO/({letter}|{digit})*=({letter}|{digit})*,}
\]

recognizes the keyword **DO** in the string **D05I=1,25**

\[\text{\textsuperscript{12}slide by John Werth.}\]
Auxiliary Procedures\textsuperscript{13}

In this third section the user may insert any desired code in the generated program.

This typically will include symbol table routines of some kind. These routines will use/work with the lex-defined globals \texttt{yylval}, \texttt{yytext}, and \texttt{yyleng}.

\textsuperscript{13}slide by John Werth.
Parser Overview

The *Parser* is a central part of a compiler.

- The input to the parser is the output of the lexical analyzer (*gettoken()* or *yylex()*).
- The parser analyzes whole statements of the program:
  
  ```
  if expression then statement else statement
  ```
- Since the language constructs may be recursive, a context-free grammar must be used.
- The parser builds complex tables, such as the symbol table, in response to declaration statements. These tables are used later in the generation of code.
- The output of the parser is *intermediate code*. 
Context Free Languages

Productions: \( A \rightarrow \alpha \)
\( A \in N \)
\( \alpha \in V^* \)  em i.e. any string

- Since left-hand-side of each production is a single nonterminal, every derivation is a tree.
- Many good parsers are known. Parsing requires a recursive program, or equivalently, a stack for temporary storage.
- Parsing time is at worst \( O(n^3) \), though programming languages are commonly \( O(n) \).
- Used for language elements that can contain themselves, e.g.,
  - Arithmetic expressions can contain subexpressions: \( A + B \times (C + D) \).
  - A noun phrase can contain a prepositional phrase, which contains a noun phrase:
    \( a\ girl\ with\ a\ hat\ on\ her\ head\).
- Any language that requires counting must be at least context free: \( a^n b^n \), balanced parentheses.
Context Sensitive Languages

Productions: \( \alpha \rightarrow \beta \)
\[
\alpha \in V^* NV^* \\
\beta \in V^+ \\
|\alpha| \leq |\beta|
\]

The strings around the \( N \) on the left-hand side of the production are the context, so a production works only in a particular context and is therefore context sensitive.

- Context sensitivity seems applicable for some aspects of natural language, e.g., subject-verb agreement.
  
  John likes Mary.
  *  John like Mary.

- No effective parsing algorithm is known.

- Parsing is NP-complete, i.e., may take exponential time, requires a search.

- Context sensitive languages are not used much in practice.
Derivations

A *derivation* is the process of deriving a sentence from the start symbol $S$ according to a grammar, *i.e.*, the replacement of nonterminal symbols by the right-hand sides of productions.

We use the symbol $\Rightarrow$ to denote a derivation step.

$$E \Rightarrow -E \Rightarrow -(E) \Rightarrow -(id)$$

demostrates the steps in deriving the expression $-(id)$ using an expression grammar.

$\Rightarrow^*$ is used to denote derivation in zero or more steps, while $\Rightarrow^+$ is used to denote derivation in one or more steps.

In a *leftmost derivation*, the leftmost nonterminal is replaced in each step. If $S \Rightarrow^*_{lm} \alpha$, then $\alpha$ is called a *left-sentential form* of the grammar $G$. A leftmost derivation is traced by a predictive, top-down parser such as *recursive descent*.

In a *rightmost* (or *canonical*) derivation, the rightmost nonterminal is replaced in each step. A shift-reduce parser (*e.g.* YACC) traces a rightmost derivation “backwards.”
Language Generated by a Grammar

Given a grammar $G$ with start symbol $S$, the language generated by $G$, denoted $L(G)$, is the set of derivable terminal strings $w$:

$$L(G) = \{ w \mid S \Rightarrow^* w \}$$

Two grammars that generate the same language are equivalent.

$$a^*b^*(a|b)^* = (a|b)^*$$

The union of two languages is simply set union, i.e.,

$$L_1 \cup L_2 = \{ l \mid l \in L_1 \lor l \in L_2 \}$$

The concatenation of two languages is:

$$L_1L_2 = \{ l_1l_2 \mid l_1 \in L_1 \land l_2 \in L_2 \}$$
Ambiguity and Left Recursion

Many derivations could correspond to a single parse tree. A grammar for which some sentence has more than one parse tree is *ambiguous*. An ambiguous grammar can be dealt with in two ways:

- Rewrite the grammar to be one that generates the same language but is unambiguous. For example, the *if-then-else* ambiguity can be eliminated.

- Use disambiguating rules to guide the parser. LEX and YACC have defaults that handle many common cases correctly. Operator precedence parsing is a form of disambiguating rules.

A grammar is *left recursive* iff $A \Rightarrow A\alpha$ for some nonterminal $A$. A left recursive grammar can cause a top-down recursive descent parser to go into an infinite loop. Left recursion can be eliminated by *left factoring* to obtain an equivalent grammar.
Parsing

A parser is a program that converts a linear string of input words into a structured representation that shows how the phrases (substructures) are related and shows how the input could have been derived according to the grammar of the language.

Finding the correct parsing of a sentence is an essential step towards extracting its meaning.

There are several different kinds of parsers:

- Top-down
- Bottom-up
- Chart
- Augmented transition network
**Top-down Parser**

A *top-down* parser begins with the Sentence symbol, $S$, expands a production for $S$, and so on recursively until words (terminal symbols) are reached. If the string of words matches the input, a parsing has been found.$^{14}$

This approach to parsing might seem hopelessly inefficient. However, *top-down filtering*, that is, testing whether the next word in the input string could begin the phrase about to be tried, can prune many failing paths early.

For languages with *keywords*, such as programming languages or natural language applications, top-down parsing can work well. It is easy to program.

---

$^{14}$See the Language Generation slide earlier in this section.
Bottom-up Parsing

In *bottom-up* parsing, words from the input string are reduced to phrases using grammar productions:

\[
\begin{array}{c}
<\text{NP}> \\
/ \ \backslash \\
<\text{art}> \quad <\text{noun}> \\
| \quad | \\
The \quad \text{man} \quad \text{ate} \quad \text{fish}
\end{array}
\]

This process continues until a group of phrases can be reduced to $S$. 
**Chart Parser**

A *chart parser* is a type of bottom-up parser that produces all parses in a triangular array called the *chart*; each chart cell contains a set of nonterminals. The bottom level of the array contains all possible parts of speech for each input word. Successive levels contain reductions that span the items in levels below: cell $a_{i,k}$ contains nonterminal $N$ iff there is a parse of $N$ beginning at word $i$ and spanning $k$ words.

<table>
<thead>
<tr>
<th></th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>NP</td>
</tr>
<tr>
<td>2</td>
<td>NP</td>
</tr>
<tr>
<td>1</td>
<td>Art</td>
</tr>
<tr>
<td>0</td>
<td>The</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

The chart parser eliminates the redundant work that would be required to reparse the same phrase for different higher-level grammar rules.

The Cocke-Kasami-Younger (CKY) parser is a chart parser that guarantees to parse any context-free language in at most $O(n^3)$ time.
Augmented Transition Network Grammars

A grammar can be written in network form. Branches are labeled with parts of speech or phrase names. Actions, such as constructing a database query, can be taken as arcs are traversed.

ATN’s are more readable than lists of productions; they can easily be coded in Lisp.
Augmented Transition Networks

An ATN is like a finite state transition network, but is augmented in three ways:

1. **Arbitrary tests** can be added to the arcs. A test must be satisfied for the arc to be traversed. This allows, for example, tests on agreement of a word and its modifier.

2. **Structure-building actions** can be added to the arcs. These actions may save information in *registers* to be used later by the parser, or to build the representation of the meaning of the sentence. Transformations, e.g., active/passive, can also be handled.

3. **Phrase names**, as well as part-of-speech names, may appear on arcs. This allows a grammar to be called as a subroutine.

The combination of these features gives the ATN the power of a Turing Machine, i.e., it can do anything a computer program can do.

---

Context Free Parser

A parser for a Context Free language converts a linear string of input tokens into a parse tree.

Any program that deals with a tree needs a stack to maintain the list of ancestors of the current node, either as:

- a recursive program: e.g., expression parser calls itself as a subroutine
- a program that maintains a stack.

These are equivalent: as we shall see, a recursive program is implemented using a runtime stack.
Semantics Influences Parsing

**Example:** Operator Precedence:

\[ A + B * C \]

means: \[ A + (B * C) \]

not: \[ (A + B) * C \]

**Possible solutions:**

1. Unambiguous operator precedence grammar.
   *Large, ugly grammar and parser.*
   In Pascal, the grammar is not large, but lack of precedence forces the programmer to parenthesize:

   \[ \text{if } ( x > y \&\& y > z ) \ldots \]

   \[ \text{if } x > y \text{ and } y > z \text{ then } \ldots \]

   The Pascal version shown above generates an error; it must be written as:

   \[ \text{if } (x > y) \text{ and } (y > z) \text{ then } \ldots \]

2. Ambiguous grammar; *precedence* guides parser.
   *Short, simple, clean grammar and parser.*
Arithmetic Expressions

Example: \((A + B) \times C + D\)

Ambiguous grammar:

\[
egin{align*}
E & \rightarrow \text{identifier} | \text{number} \\
OP & \rightarrow + | - | \times | / \\
E & \rightarrow E \ OP \ E \\
E & \rightarrow (E)
\end{align*}
\]

Unambiguous grammar:

\[
egin{align*}
E & \rightarrow E + T \mid E - T \\
E & \rightarrow T \\
T & \rightarrow T \times F \mid T / F \\
T & \rightarrow F \\
F & \rightarrow (E) \\
F & \rightarrow \text{identifier} \mid \text{number}
\end{align*}
\]

\(E, T, F\) stand for \textit{expression}, \textit{term}, and \textit{factor}. 
Example of Operator Precedence

An operator precedence parser examines the current operator and the preceding operator on the stack to decide whether to *shift* the current operator onto the stack or to *reduce* (group) the preceding operator and its operands.

```
1 2 3 4 5 6 7 8
A + B * C + D
```

<table>
<thead>
<tr>
<th>Pos</th>
<th>Operand Stack</th>
<th>Operator Stack</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>A B</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>A B</td>
<td>+ *</td>
</tr>
<tr>
<td>5</td>
<td>A B C</td>
<td>+ *</td>
</tr>
<tr>
<td>6</td>
<td>A (* B C)</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>(+ A (* B C))</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(+ A (* B C))</td>
<td>+</td>
</tr>
<tr>
<td>7</td>
<td>(+ A (* B C)) D</td>
<td>+</td>
</tr>
<tr>
<td>8</td>
<td>(+ (+ A (* B C)) D)</td>
<td></td>
</tr>
</tbody>
</table>
```
Operator Precedence

Expressions could be written in an unambiguous, fully parenthesized form. However, this is less convenient for the programmer.

*Precedence* specifies which operations in a flat expression are to be performed first. $B \times C$ is performed first in $A + B \times C$; $\times$ takes precedence over $+, \times \succ +$.

*Associativity* specifies which operations are to be performed first when adjacent operators have the same precedence. $A + B$ is performed first in $A + B + C$ since $+$ is *left-associative*. $B ** C$ is performed first in $A ** B ** C$ since $**$ is *right-associative*.

Typical precedence values [*not* Pascal]:

1. $:$ (highest precedence)
2. $^\dagger$
3. $-$ (unary)
4. $\ast, /$
5. $+,$
6. $=,<,\geq,\leq,<$
7. $\neg$
8. $\text{and}$
9. $\text{or}$
10. $:= $ (lowest precedence)
Operator Precedence Parsing

Operator precedence parsing is easily done using auxiliary stacks for operands and operators. Tokens are read and processed as follows:

- **Operands**: push (shift) onto the operand stack.
- **Operators**:
  - While $\text{prec}(\text{top}(\text{stack})) \geq \text{prec}(\text{input})$, **reduce**.
  - Push (shift) $\text{input}$ onto the operator stack.
- $($: Push ( onto the operator stack; $\text{prec}(()) < \text{prec(any operator)}$.
- $)$: While $\text{top}(\text{stack}) \neq (, \text{reduce}$.
  - Then discard both parentheses.
- **End**: While operator stack is not empty, **reduce**.
  - Result is top of operand stack.

**reduce** combines the two top operands and the top operator into a subtree, which is pushed onto the operand stack.

The $=$ part of the $\geq$ test for operators implements left associativity, the usual case. For right associativity, use $>$ instead.
## Operator Precedence Parsing

### A + B * C

<table>
<thead>
<tr>
<th>op</th>
<th>operand</th>
<th>input</th>
<th>action</th>
<th>why</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A + B * C</td>
<td>start</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>+ B * C</td>
<td>shift A</td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>A</td>
<td>B * C</td>
<td>shift +</td>
<td>empty &lt; +</td>
</tr>
<tr>
<td>+</td>
<td>A B</td>
<td>* C</td>
<td>shift B</td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>* A B</td>
<td>C</td>
<td>shift *</td>
<td>+ &lt; *</td>
</tr>
<tr>
<td>+</td>
<td>* A B C</td>
<td></td>
<td>shift C</td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>A (* B C)</td>
<td></td>
<td>reduce</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(+ A (* B C))</td>
<td></td>
<td>reduce</td>
<td></td>
</tr>
</tbody>
</table>

### A * B + C

<table>
<thead>
<tr>
<th>op</th>
<th>operand</th>
<th>input</th>
<th>action</th>
<th>why</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A * B + C</td>
<td>start</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>* B + C</td>
<td>shift A</td>
<td></td>
</tr>
<tr>
<td>*</td>
<td>A</td>
<td>B + C</td>
<td>shift *</td>
<td>empty &lt; *</td>
</tr>
<tr>
<td>*</td>
<td>A B</td>
<td>+ C</td>
<td>shift B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(* A B)</td>
<td>+ C</td>
<td>reduce</td>
<td>* ≥ +</td>
</tr>
<tr>
<td>+</td>
<td>(* A B)</td>
<td>C</td>
<td>shift +</td>
<td>empty &lt; +</td>
</tr>
<tr>
<td>+</td>
<td>(* A B) C</td>
<td></td>
<td>shift C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(+ (* A B) C)</td>
<td></td>
<td>reduce</td>
<td></td>
</tr>
</tbody>
</table>
### Operator Precedence Parsing...

\[(A + B) * C\]

<table>
<thead>
<tr>
<th>operator</th>
<th>operand</th>
<th>input</th>
<th>action</th>
<th>why</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(A + B) * C</td>
<td>start</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td></td>
<td>A + B) * C</td>
<td>shift (</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>A</td>
<td>+ B) * C</td>
<td>shift A</td>
<td></td>
</tr>
<tr>
<td>( +</td>
<td>A</td>
<td>B) * C</td>
<td>shift +</td>
<td>(&lt; +</td>
</tr>
<tr>
<td>( +</td>
<td>A B</td>
<td>) * C</td>
<td>shift B</td>
<td></td>
</tr>
<tr>
<td>( +</td>
<td>A B</td>
<td>* C</td>
<td>reduce, ()</td>
<td></td>
</tr>
<tr>
<td>*</td>
<td>(+ A B)</td>
<td>C</td>
<td>shift *</td>
<td>empty &lt; *</td>
</tr>
<tr>
<td>*</td>
<td>(+ A B)</td>
<td>C</td>
<td>shift C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(* (A B) C)</td>
<td>reduce</td>
<td></td>
</tr>
</tbody>
</table>
Operator Precedence Parser

(defun expr (inp) ; opprecc.lsp
  (let (token *op-stack* *opnd-stack*)
    (while inp
      (setq token (pop inp))
      (if (consp token) ; (exp)
        (push (expr token) *opnd-stack*)
        (if (operatorp token)
          (progn
            (while
              (>= (prec (first *op-stack*))
                (prec token))
              (reducex))
            (push token *op-stack*)))
          (push token *opnd-stack*)))
    (while *op-stack* (reducex))
    (pop *opnd-stack*))
  )

; Reduce top of stacks to operand
(defun reducex ()
  (let ((rhs (pop *opnd-stack*)))
    (push (list (pop *op-stack*) ; op
                (pop *opnd-stack*) ; lhs
                rhs) ; rhs
         *opnd-stack*)
  ))
Examples

(expr `(a + b) )

==> (+ A B)

(expr `(x := a + b * c) )

==> (= X (+ A (* B C)))

(expr `(x := a * b + c) )

==> (= X (+ (* A B) C))

(expr `(x := (a + b) * (c + d * e) + f) )

==> (= X (+ (* (+ A B) (+ C (* D E))) F))
Stack Handling in C

- **Initialize** a stack \( s \) to Empty:
  \[
  s = \text{NULL};
  \]

- **Test** if stack \( s \) is not Empty:
  \[
  \text{if} \ ( s \neq \text{NULL} ) \ldots
  \]

- **Push** an item \( \text{newtok} \) onto stack \( s \):
  \[
  \text{newtok->link} = s;
  s = \text{newtok};
  \]
  or:
  \[
  s = \text{cons(newtok,s)};
  \]

- **Pop** stack \( s \) to yield item \( \text{top} \):
  \[
  \text{top} = s;
  s = s->\text{link}; \quad /* s = \text{rest(s)} */
  \]
Basic Routines

TOKEN opstack, opndstack;

    /* + - * / ... */
int opprec[20] = { 0, 6, 6, 7, 7, ...};

void pushop (TOKEN tok) /* push op onto stack */
    { tok->link = opstack;
      opstack = tok;  }

TOKEN popop () /* pop op from stack */
    { TOKEN tok;
      tok = opstack;
      opstack = tok->link;
      return(tok);  }

int prec (TOKEN tok) /* precedence of op tok */
    { if (tok == NULL)
      return(-1);    /* -1 for empty stack */
    else if (tok->tokentype == OPERATOR)
      return(opprec[tok->whichval]);
    else return(-1);  } /* -1 for ( */
reduceop () /* reduce binary op */
{
    TOKEN op, lhs, rhs;
    rhs = popopnd(); /* rhs at top */
    lhs = popopnd();
    op = popop();
    op->operands = lhs; /* first child */
    lhs->link = rhs; /* next sibling */
    rhs->link = NULL; /* null terminate */
    pushopnd(op); } /* subtree now operand */

We use the first child - next sibling form of tree; this represents an arbitrary tree using only two pointers. The tree form of a binary operator and operands is:

    op
     /
    /  
operands /
     /  
     /   
     /    
     /     
     /      
     link
lhs ----------> rhs

Down arrows are always operands; side arrows are always link. The pretty-printer will print this as:

    (op lhs rhs)
Operator Precedence Parser

TOKEN expr ()
{
    int done;
    TOKEN tok;
    done = 0;
    opstack = NULL;
    opndstack = NULL;
    while (done == 0)
    {
        tok = gettoken();
        if (EOFFLG == 0)
            switch (tok->tokentype)
            {
                case IDENTIFIERTOK: case NUMBERTOK:
                    pushopnd (tok); break;
                case DELIMITER:
                    if (tok->whichval == LPARENTHESIS)
                        pushop (tok);
                    else if (tok->whichval == RPARENTHESIS)
                        { while (opstack->whichval != LPARENTHESIS)
                            reduceop();
                            popop();
                        }
                    else done = 1;
                    break;
            }
}
case RESERVED:
    done = 1;
    break;
  case OPERATOR:
      while (prec(tok) <= prec(opstack))
          reduceop();
      pushop(tok);
      break;
  }
  else done = 1;
}
while (opstack != NULL) reduceop();
return (opndstack);  }
Additional Considerations

1. Error checking. A current status variable that tracks the type of the previous token is helpful.
   - Previous token was ( or start
   - Previous token was an operator
   - Previous token was an operand

2. Unary operators, such as unary minus. In the proper context, minus can be converted into a different operator that represents unary-minus.

3. Right-associative operators. Shift when the top-of-stack has the same precedence if the operator is right-associative.

4. Type checking and coercion.

5. Function calls. These can be treated like parenthesized subexpressions, keeping track of the number of arguments.

6. Array subscripts. These can be treated like function calls, then modified to perform subscript calculations.
Recursive Descent Parser

A parser for some context-free languages can be written using the technique of *recursive descent*. The basic idea is to write a procedure to parse each kind of statement or expression in the grammar. When such procedures are written in a recursive language, they can call each other as needed.

**Example:**

\[
\text{if } expression \text{ then statement else statement}
\]

Recursive descent works well for a well-structured language such as Pascal. In Pascal, each statement other than assignment statements begins with a unique reserved word; thus, it is easy for a “big switch” program to determine which statement parser to call.

It may be necessary to restructure a grammar to avoid *left recursion*, which can cause a recursive descent parser to go into a loop.

Operator precedence can be used for arithmetic expressions.
Bottom-up Table-driven (LR) Parsing

The most general form of this technique can be used for any language which can be recognized by a deterministic push down automaton.

As one might expect, the parser consists of a stack and a state machine which is derived from the grammar. The overall model is the following:\textsuperscript{16}

\textsuperscript{16}Aho, Lam, Sethi, and Ullman, \textit{Compilers}, Fig. 4.35.
The LR Parsing Algorithm\textsuperscript{17}

A configuration of an LR parser is a pair whose first component is the stack contents and whose second component is the unexpended input:

\[(S_0X_1S_1X_2S_2...X_mS_m, a_ja_{j+1}...a_n\$)\]

This configuration represents the right-sentential form:

\[(X_1X_2...X_m a_ja_{j+1}...a_n)\]

The next move of the parser is determined by reading \(a_j\), the current input symbol, and \(S_m\), the state on top of the stack, and then consulting the parsing action table entry, \(\text{action}[S_m, a_j]\).

\textsuperscript{17}slide by John Werth
Shift-Reduce Parser

Based on the current state and current input, \( action[S_m, a_j] \) gives one of four possible actions:

- **Shift** \( s \): Shift the current input \( a_j \) onto the stack and go to the specified next state \( s \).

- **Reduce** \( r \): Given the production \( r : A \rightarrow \beta \), remove enough items from the stack to match \( \beta \), produce output structure from those items, and put the resulting structure \( A \) back on the stack. The next state is found from the \( goto \) table.

- **Accept**: Parsing is completed; return top of stack as result.

- **Error**: The input cannot be parsed according to the grammar; call an error recovery routine. Error entries are denoted by blanks in the parsing table.
Example Parsing Table\textsuperscript{18}

1. $E \rightarrow E + T$
2. $E \rightarrow T$
3. $T \rightarrow T * F$
4. $T \rightarrow F$
5. $F \rightarrow (E)$
6. $F \rightarrow id$

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\textbf{State} & \textbf{id} & \textbf{+} & \textbf{*} & \textbf{(} & \textbf{)} & \textbf{$\$} & \textbf{goto} \\
\hline
0 & s5 & s4 & & & & 1 & 2 & 3 \\
1 & s6 & & & & acc & & & \\
2 & r2 & s7 & r2 & r2 & & & & \\
3 & r4 & r4 & r4 & r4 & & & & \\
4 & s5 & s4 & & & & 8 & 2 & 3 \\
5 & r6 & r6 & r6 & r6 & & & & \\
6 & s5 & s4 & & & & 9 & 3 & & \\
7 & s5 & s4 & & & & & 10 & & \\
8 & s6 & & & s11 & & & & \\
9 & r1 & s7 & r1 & r1 & & & & \\
10 & r3 & r3 & r3 & r3 & & & & \\
11 & r5 & r5 & r5 & r5 & & & & \\
\hline
\end{tabular}
\end{table}

\textsuperscript{18}Aho, Lam, Sethi, and Ullman, \textit{Compilers}, Fig. 4.37, p. 252.
A Parse of $id \times id + id^{19}$

<table>
<thead>
<tr>
<th>Stack</th>
<th>Input</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 0</td>
<td>$id \times id + id$</td>
<td>shift</td>
</tr>
<tr>
<td>(2) 0 id 5</td>
<td>$\times id + id$</td>
<td>reduce by $F \rightarrow id$</td>
</tr>
<tr>
<td>(3) 0 F 3</td>
<td>$\times id + id$</td>
<td>reduce by $T \rightarrow F$</td>
</tr>
<tr>
<td>(4) 0 T 2</td>
<td>$\times id + id$</td>
<td>shift</td>
</tr>
<tr>
<td>(5) 0 T 2 7</td>
<td>id + id$</td>
<td>shift</td>
</tr>
<tr>
<td>(6) 0 T 2 7 id 5</td>
<td>+ id$</td>
<td>reduce by $F \rightarrow id$</td>
</tr>
<tr>
<td>(7) 0 T 2 7 F 10</td>
<td>+ id$</td>
<td>reduce by $T \rightarrow T*F$</td>
</tr>
<tr>
<td>(8) 0 T 2</td>
<td>+ id$</td>
<td>reduce by $E \rightarrow T$</td>
</tr>
<tr>
<td>(9) 0 E 1</td>
<td>+ id$</td>
<td>shift</td>
</tr>
<tr>
<td>(10) 0 E 1 + 6</td>
<td>id$</td>
<td>shift</td>
</tr>
<tr>
<td>(11) 0 E 1 + 6 id 5</td>
<td>$</td>
<td>$</td>
</tr>
<tr>
<td>(12) 0 E 1 + 6 F 3</td>
<td>$</td>
<td>$</td>
</tr>
<tr>
<td>(13) 0 E 1 + 6 T 9</td>
<td>$</td>
<td>$</td>
</tr>
<tr>
<td>(14) 0 E 1</td>
<td>$</td>
<td>$</td>
</tr>
</tbody>
</table>

\[^{19}\text{Aho, Lam, Sethi, and Ullman, } Compilers, \text{ Fig. 4.38, p. 253.}\]
Synthesized Translation

The term *synthesized translation* includes two ideas:

- A complex expression is constructed from subexpressions.

  \[ \text{if expression then statement} \]

- The translation of a complex expression is constructed in a mechanical way from the translations of its subexpressions.

In the statement \( \text{if } x > \text{max} \text{ then max } := x \) the code for the \textbf{if} statement is constructed by linking together the code that is produced for the subexpressions \( x > \text{max} \) and \( \text{max } := x \).

\[
\begin{align*}
> & := \\
& / / \text{ operands} \\
& / / \\
x & ---- \text{max} \quad \text{max } ---- x \\
& \text{link} \\
& \text{if} \ (\text{if } (> \ x \ \text{max}) \ (:= \ \text{max } \ x)) \\
& / \\
& / \\
& > \text{------------} \ := \\
& / / \\
& / / \\
x & ---- \text{max} \quad \text{max } ---- x
\end{align*}
\]
Using yacc

**yacc** compiles an input file (with `.y` suffix), always producing the output file **y.tab.c** (a C file that can be compiled to an executable using the C compiler).

**y.tab.c** contains:

- a table-driven parser,
- tables compiled from the input file’s grammar rules,
- the C code from the input file.

The parser in **y.tab.c** is designed to call a lexical analyzer produced by **lex**. The user’s C code will contain the **main()** program; **main()** calls the code generator as a subroutine after parsing is complete.
The file `y.tab.c` produced by YACC has the following structure:

<table>
<thead>
<tr>
<th>User’s C code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parsing Tables from user’s grammar</td>
</tr>
<tr>
<td>“Canned” LR Parser in C</td>
</tr>
<tr>
<td>Action code from user’s grammar</td>
</tr>
</tbody>
</table>
Yacc Specifications

{%{ declarations %}

tokens

%%%

translation rules

%%%

auxiliary procedures

• declarations: #include and manifest constants (identifier declared to represent a constant).

• tokens: %token declarations used in the second section. Each token is defined as a constant (integer > 255).

• translation rules: pattern / action pairs

• auxiliary procedures: arbitrary C functions copied directly into the generated parser.

\footnote{\textsuperscript{20}slide by John Werth.}
Example: Desk Calculator

```c
/* simcalc.y -- Simple Desk Calculator */
/* Aho, Sethi & Ullman, Compilers, Fig. 4.56 */
#include <ctype.h>
#include <stdio.h>
%
%token DIGIT /* = #define DIGIT 257 */
%
line : expr '
' { printf("%d\n", $1); } ;
expr : expr '+' term { $$ = $1 + $3; } | term ;
term : term '*' factor { $$ = $1 * $3; } | factor ;
factor: '(' expr ')' { $$ = $2; } | DIGIT ;
%
yylex() {
    int c;
    c = getchar();
    if (isdigit(c)) {
        yylval = c - '0';
        return DIGIT;
    }
    return c;
}
```
Yacc: Pascal Subset

program : statement DOT /* change this! */
  { parseresult = $1; } ;
statement : BEGINBEGIN statement endpart
  { $$ = makeprogn($1,cons($2,$3)); } |
  IF expr THEN statement endif
  { $$ = makeif($1, $2, $4, $5); } |
  assignment ;
endpart : SEMICOLON statement endpart
  { $$ = cons($2, $3); } |
  END { $$ = NULL; } ;
endif : ELSE statement { $$ = $2; }
  | /* empty */ { $$ = NULL; } ;
assignment : variable ASSIGN expr
  { $$ = binop($2, $1, $3); } ;
expr : expr PLUS term
  { $$ = binop($2, $1, $3); } |
  term ;
term : term TIMES factor
  { $$ = binop($2, $1, $3); } |
  factor ;
factor : LPAREN expr RPAREN { $$ = $2; }
  | variable |
  | NUMBER ;
variable : IDENTIFIER ;
TOKEN cons(item, list) /* link item to list */
    TOKEN item, list;
    { item->link = list;
        return item;
    }

TOKEN binop(op, lhs, rhs) /* reduce binary op */
    TOKEN op, lhs, rhs;
    { op->operands = lhs; /* link opnds to op */
        lhs->link = rhs; /* link 2nd operand */
        rhs->link = NULL; /* terminate opnds */
        return op;
    }

TOKEN makeprogn(tok, statements) /* make progn */
    TOKEN tok, statements;
    { tok->tokentype = OPERATOR; /* change tok */
        tok->whichval = PROGNOP; /* to prog*/
        tok->operands = statements;
        return tok;
    }
TOKEN makeif(tok, exp, thenpart, elsepart)

TOKEN tok, exp, thenpart, elsepart;
{
    tok->tokentype = OPERATOR; /* change tok */
    tok->whichval = IFOP;      /* to if op */
    if (elsepart != NULL)
        elsepart->link = NULL;
    thenpart->link = elsepart;
    exp->link = thenpart;
    tok->operands = exp;
    return tok;
}

if (if exp
    /
    / thenpart
    / operands
    / elsepart)
    /
    /
    exp -------> thenpart -------> elsepart
    link      link

98
Controllability and Observability

These are central concepts from control theory. We will define them as:

- **Controllability**: the ability to change the behavior of a system by changing its parameters.
- **Observability**: the ability to observe the state and behavior of a system well enough to control it.

In order to control a system, both controllability and observability are required.

The implications for large software systems are:

- Aspects of software that cannot easily be observed will never be debugged.
- All large software systems must have observability built in.
- Observability is a requirement, not a luxury. The time spent building in observability will be well repaid.
- In-process traces can be turned on by setting bits in a bit vector.
Example

i:=j.  /* input */

binop
  79220  OP := link 0 operands 79172
  79172  ID I link 79268
  79268  ID J link 0

yyparse result = 0  /* means "no error" */
  79220  OP := link 0 operands 79172

(:= I J)

:=
/
/ operands
/
/
/

i --------> j
  link
Examples ...

begin i:=j; j:=7 end. /* input */

binop
79460 OP := link 0 operands 79412
79412 ID I link 79508
79508 ID J link 0

binop
79652 OP := link 0 operands 79604
79604 ID J link 79700
79700 NUM 7 link 0

cons
79652 OP := link 0 operands 79604
0 NULL

cons
79460 OP := link 79652 operands 79412
79652 OP := link 0 operands 79604

makeprogn
79364 OP progn link 0 operands 79460
79460 OP := link 79652 operands 79412

yyparse result = 0
79364 OP progn link 0 operands 79460

(progn (:= I J)
   (:= J 7))
Examples ...

if i+j then begin i:=j; j:=3 end else k:=i .

binop 79940 OP +, ID I, ID J
binop 80180 OP :=, ID I, ID J
binop 80372 OP :=, ID J, NUM 3
cons 80372 OP :=, 0 NULL
cons 80180 OP :=, 80372 OP :=
makeprogn
  80084 OP progn, 80180 OP :=
binop 80612 OP :=, ID K, ID I
makeif
  79844 OP if link 0 operands 79940
  79940 OP + link 80084 operands 79892
  80084 OP progn link 80612 operands 80180
  80612 OP := link 0 operands 80564
yyparse result = 0
79844 OP if link 0 operands 79940
(if (+ I J)
  (progn (= I J)
    (= J 3))
  (= K I))
Hints for yacc

Some useful hints for using yacc:

- Avoid “empty” productions; these are likely to generate grammar conflicts that may be hard to find. Each production should consume some input.

- Follow the Pascal grammar flowcharts exactly. If you just write the grammar from your memory of Pascal syntax, it probably won’t work.

- When the action code for a production is called, all of the $i$ variables have been completely processed and have values.

- If you need to process a list of items of the same kind, the code for begin is a good model.

- The yacc stack has a single type; for our program, that type is TOKEN. If you want to return something else (e.g. a SYMBOL), package it in a TOKEN as symtype.
program <----- parseresult

graph1 -- progn -- progn

output := --- progn

lim -- 7 := ---- label -- if

i -- 0 0 <= ----- progn

i -- lim funcall ----- := ---- goto

writeln -- '*' i -- + 0

(program graph1 (progn output)
 (progn (:= lim 7)
  (progn (:= i 0)
   (label 0)
   (if (<= i lim)
    (progn (funcall writeln '*)
     (:= i (+ i 1))
     (goto 0)))))

i -- 1
The Semantic Actions\textsuperscript{21}

Semantic actions refer to the elements of the production by a positional notation. $\$$\$$ denotes the left side nonterminal. $\$$n refers to the nth symbol on the right-hand side.

For example:

\[ \text{expr : expr } '+' \text{ term } \{ \$$ = $1 + $3; \} \]

The default action action is \{ $\$$ = $1; \}. For this reason, we do not need to have an explicit action for

\[ \text{expr : term} \]

\textsuperscript{21}slide by John Werth.
Supporting C Routines\textsuperscript{22}

A lexical analyzer named \texttt{yylex()} must be provided in the third section. This can be user-written or generated by lex.

\texttt{yylex} must return \textit{two} values:

- “what is it?” , a small integer that is the return value, e.g. \texttt{return(NUMBER)};
- the actual value of the item, by setting the value of \texttt{yylval}, e.g. \texttt{yylval = tok};

\textsuperscript{22}adapted from slide by John Werth.
Example

```c
/* Aho, Lam, Sethi, Ullman, Compilers: Fig. 4.59 */
#include <ctype.h>
#include <stdio.h>
#define YYSTYPE double /* double type for yacc stack */

%token NUMBER
%left '+' '-',
%left '*', '/'
%right UMINUS

lines: lines expr '
' { printf("%f\n",$2); }
    | lines '
'
    | /* epsilon */
    | error '
' {yyerror("reenter last line:"),
            yyerrok; }
        ;
expr: expr '+' expr { $$ = $1 + $3; }
    | expr '-' expr { $$ = $1 - $3; }
    | expr '*' expr { $$ = $1 * $3; }
    | expr '/' expr { $$ = $1 / $3; }
    | '(' expr ')' { $$ = $2; }
    | '-' expr %prec UMINUS { $$ = - $2; }
    | NUMBER
    ;

yylex() {
    int c;
    while ( (c = getchar()) == ' ');
    if ( (c == '.') || (isdigit(c)) ) {
        ungetc(c, stdin);
        scanf("%lf", &yylval);
        return NUMBER;
    }
    return c; }

yyerror(s)
    char * s;
    { fputs(s,stderr), putc(\n', stderr); }

main() /* Call repeatedly to test */
    { int res;
      while (1) { res = yyparse(); } }
```
Comments on the Example\textsuperscript{23}

The statement \texttt{#define YYSTYPE double} sets \texttt{YYSTYPE}, the type of the yacc semantic stack. This stack parallels the syntax stack maintained by the LALR parser. References like \texttt{$1$} to values in the the right hand side of a production are actually references to this stack of values. This stack could have record type or union type; the latter is typical for a compiler.

Note that a grammar may be ambiguous, with parsing action conflicts; yacc will report this.

To see the sets of items and the specific parsing action conflicts, use the \texttt{yacc -v} option. The diagnostic information will be produced in a file called \texttt{y.output}.

\texttt{yacc -v parse.y}

\textsuperscript{23}slide by John Werth.
Parsing Action Conflicts

Parsing action conflicts are not necessarily fatal; yacc resolves them using the following default rules:

- reduce/reduce is resolved by choosing the first listed production.
- shift/reduce is resolved in favor of shift.

A more general mechanism used to resolve shift reduce is to associate a precedence and associativity to both productions and terminal.

Precedence of terminal depends on the order in which it appears in the specification: for example, * is higher than + in the earlier example.

The precedence and associativity of a production is that of the rightmost terminal by default. It can be set with \%prec to that of any terminal. For example,

\[
\text{expr : } '-' \text{ expr } \%\text{prec UMINUS}
\]

sets the production associativity and precedence to that of UMINUS.

---

\(^{24}\text{slide by John Werth.}\)
Resolving Shift/Reduce Conflicts

The rule for reducing shift/reduce conflicts is:

- **reduce** if the precedence of the production is greater than that of the terminal or if they are equal and the associativity of the production is left.

- **shift** otherwise.

Our Pascal grammar has a shift/reduce conflict in the case of the *if* statement; these rules resolve it in favor of shift, which does the right thing.
Error Productions

The earlier example grammar contains an error production:

\[
\text{lines : error 'n' \{ yyerror("reenter last line:"); yyerrok; \}}
\]

An error production uses the keyword error followed by a string: \[ A : error \alpha \]
\[ yyerrok \] resets the parser so it can continue.

\(^{26}\)slide by John Werth.
Error Handling

During the parse, if an error is encountered (access to a blank entry in the LALR table) the following happens:

1. the stack is popped until a state is on top whose items match the right-hand side of an error production.
2. a token error is shifted onto the stack
3. if $\alpha$ is empty, then a reduction takes place and the semantic action is performed.
4. if $\alpha$ is non-empty, the parser tries to identify $\alpha$ in the input. It then pushes $\alpha$ on the stack and does a reduction as usual.

For example, $\text{stmt : error }';;$' will have the effect of causing the parser to skip ahead to the next ; and assume that a statement has been found.

---

27 slide by John Werth.
Parsing Techniques

Recursive Descent and Operator Precedence:

- **Advantages:**
  - Easy to control, understand.
  - Good error messages can be produced.
- **Disadvantages:**
  - More code to write.
  - Grammar not as clear.
  - Does the program really match the grammar?

**Parser Generator: yacc**

- **Advantages:**
  - Less code to write.
  - Grammar is clear and easy to change.
- **Disadvantages:**
  - The programmer may get “stuck” on grammar errors that are hard to understand.
  - Error messages during compilation may be unhelpful and far from the actual error.
Looping Statements

Looping statements generate multiple statements in intermediate code, as shown in the following patterns. (Generate label numbers by \( j = \text{labelnumber}++; \))

for \( i := \text{start} \) to \( \text{end} \) do \( s \)

\[
\text{(PROGN (:= i \text{start})} \\
\quad \text{(LABEL j)} \\
\quad \text{(IF (<= i \text{end})} \\
\quad \quad \text{(PROGN s} \\
\quad \quad \quad \text{(:= i (+ 1 i))} \\
\quad \quad \quad \text{(GOTO j)})})
\]

while \( c \) do \( s \)

\[
\text{(PROGN (LABEL j)} \\
\quad \text{(IF c (PROGN s (GOTO j))))}
\]

repeat statements until \( c \)

\[
\text{(PROGN (LABEL j)} \\
\quad \text{(PROGN statements)} \\
\quad \text{(IF c (PROGN) (GOTO j))})
\]

The empty \( \text{(PROGN)} \) acts as a no-op.
Symbol Table

A symbol table is a map data structure that associates names with information about the objects that are denoted by the names.

Programming languages have many kinds of symbols: statement labels, variables, constants, subprogram names, etc.

A symbol table must be well organized:

- For fast lookup of symbols.
  Note that if symbol table lookup takes $O(n)$ time, the total compilation time becomes $O(n^2)$.
- To reflect the organization of the program (block structure).

A set of symbol table routines for use with the class programs is provided in the file `symtab.c` and documented in the file `symtab.txt`.
Symbol Table Organization

A symbol table is a set of data structures and associated procedures that allow “symbols” (perhaps defined rather broadly) and associated information to be stored and looked up.

<table>
<thead>
<tr>
<th>Symbol “key”</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information about the Symbol</td>
<td></td>
</tr>
</tbody>
</table>

Operations:

- **Insert**: Insert a new symbol into the table.
- **Search**: Search for a symbol in the table.
- **Search/Insert**: Search for a symbol, Insert if not found.

We are often interested in the performance (expected time) of these operations. There are more searches than insertions.
Symbol Table Organizations

**Linear, Unsorted:**
Symbols are stored in an array; new symbols are inserted at the end.

- **Insert:** $O(1)$
- **Search:** $O(n)$ Search half the table on average.

**Linear, Sorted:**
Symbols are stored in an array that is sorted (*e.g.*, alphabetically).

- **Insert:** $O(n)$ Move half the table on average.
- **Search:** $O(\log n)$ Binary search.
Good for reserved words (no insertions).
Binary Search Tree (BST) Symbol Table

Compare search key to contents of node:

= Found
< Search left subtree
> Search right subtree

**Advantage:** $O(\log n)$ search time if tree is balanced.

**Disadvantage:** Search time may be long if tree is not balanced.
AVL Trees

An AVL Tree is a binary tree that is approximately height-balanced: left and right subtrees of any node differ in height by at most 1.

**Advantage:** Approximately $O(\log n)$ search and insert time.

**Disadvantage:** Somewhat complex code (120 - 200 lines).

---

Hash Table

Symbols are stored in a hash table, indexed by a hash function applied to the key value (e.g., multiply a symbol by itself and take some bits from the middle of the product). The hash function always produces the same value for a given symbol, but is otherwise “random”. If there is a collision (two different symbols hash to the same value), it is necessary to rehash (e.g., try the next place in the table).

Insert: $O(1)$ Depends on table fullness
Search: $O(1)$ Depends on table fullness

The expected time is short for a table that is under 70% full; time depends on fullness but not on table size.

Advantages:

- Fast
- Works for symbols without a natural sort order

Disadvantages:

- More complex code
- Have to find a good hashing function
- Must dedicate a large table, or rehash the table to expand.
Hash Functions

Not all hash functions are good; a good one should be easy to compute and should “randomize” symbols into different hash locations, not lump them into only a few hash values.

Some examples of good hash functions:

- Treat the symbol name as an integer, square it, and take some bits out of the middle.
- Treat the symbol name as an integer and find the remainder of the name modulo $p$, $\%p$, where $p$ is prime.

A typical re-hash function is simply to add 1 to the previous hash function value.
Indexed Buckets

A symbol is used to index a table, which provides a pointer to a linked list of symbols.

Hashed with Buckets:
A hashing function is used to index the table of buckets.

Insert: $O(1)$
Search: $O(n)$ Actually $n/(2 \cdot n_b)$

$n_b$ (number of buckets) can be large.

Since pointers are used for the linked list of symbols, the table can be expanded by requesting more memory.

Alphabetized Buckets:
The first character of first few characters of a symbol are used to index the table of buckets.

Insert: $O(n)$ Linked list is sorted
Search: $O(n)$ Actually $n/(2 \cdot n_b)$ Some letter combinations are much more common, so some bucket entries will be empty. Symbols are in a sorted order.
Lexical Scoping\textsuperscript{29}

\textit{Scope} is the region of program text over which a symbol can be referenced. In most languages, the scope of a variable is determined by syntax, e.g. a variable can be used only inside the procedure that defines it. This notion of scope is reflected in the symbol table, which is called \textit{lexical scoping}. With \textit{lexical scoping}, a name is defined when it can be looked up in the lexicon (symbol table) at the point of use.

Some languages (Algol, Pascal, PL/I) have allowed procedures to be nested inside other procedures and to inherit their symbols; however, this has a high runtime cost and only slight benefit.

\textsuperscript{29}adapted from slide by John Werth.
The nested procedures of the previous figure can be thought of as a tree. Each procedure can access its symbols and the symbols of its ancestors. A symbol at a lower level *shadows* any symbols with the same name at higher levels, e.g. in method overriding in OOP.

Our symbol table will have only two levels:

- Level 0: predefined symbols such as `integer`
- Level 1: symbols of the program being compiled

\[^{30}\text{adapted from slide by John Werth.}\]
Stack Symbol Table

During compilation, the compiler performs a depth-first traversal of the tree of procedures.

Since a procedure can access its symbols and the symbols of its ancestors, the symbol table could be structured as a stack.

Searching backwards through the stack implements shadowing, i.e. the closest definition of a symbol with a given name takes precedence.

When parsing of a procedure is finished, its local symbol table can be popped off the stack.

Alternatively, the whole tree of symbol tables can be maintained, with each node having a pointer to its parent.

---

adapted from slide by John Werth.
Use of Symbol Table

Usually, there are some symbols that are predefined by the language, e.g. integer. These will be put into the symbol table by the initialization of the compiler.

User symbols are added in response to declaration statements; these statements usually appear at the top of a procedure. Declaration statements often do not generate any code, but cause symbol table entries to be made and affect code generation for executable statements.

Symbols encountered in code, e.g. in assignment statements, are looked up in the symbol table. If a symbol is not found in the table, an undefined symbol error is generated. Looking up a symbol provides its type and its memory address (offset), which are needed for type checking and code generation.
Symbol Table Entry

A symbol table entry stores a variety of information about a symbol:

<table>
<thead>
<tr>
<th>link</th>
<th>Link to Next Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>namestring</td>
<td>Name of Symbol</td>
</tr>
<tr>
<td>kind</td>
<td>Kind of Symbol: VARSYM</td>
</tr>
<tr>
<td>basicdt</td>
<td>Basic Data Type: REAL</td>
</tr>
<tr>
<td>datatype</td>
<td>Pointer to Data Type</td>
</tr>
<tr>
<td>blocklevel</td>
<td>Block Nesting Level: 1</td>
</tr>
<tr>
<td>size</td>
<td>Size in bytes</td>
</tr>
<tr>
<td>offset</td>
<td>Offset from Data Area</td>
</tr>
<tr>
<td>intnum, realnum</td>
<td>Constant Value</td>
</tr>
<tr>
<td>lowbound</td>
<td>Low Bound</td>
</tr>
<tr>
<td>highbound</td>
<td>High Bound</td>
</tr>
</tbody>
</table>
Kinds of Symbols

A compiler must typically deal with several different kinds of symbols:

- Symbolic constants: `const pi = 3.1415926`
  Store constant value and type; convert an identifier with this name to a numeric constant as soon as it is looked up. The language may have some built-in symbolic constants, such as `maxint`.

- Enumerated types:
  ```
  type color = (red, white, blue);
  ```
  Simply assign constant values 0, 1, ... to the items. The name `color` becomes a subrange 0..2.

- Subrange types: `type digit = 0..9;`
  Store the associated scalar type and the lower and upper bounds (always integers).

- Scalar types:
  ```
  boolean integer real char pointer
  ```
  These are predefined as types in the symbol table.

- Variables: these may have scalar types or complex types.
Kinds of Symbols ...

- Arrays: `array[1..10] of date`
  Store the number of dimensions, lower and upper bound for each, type of array element, number of address units per element.

- Records:
  ```
  type vector = record x,y : integer end;
  ```
  Store each element name, type, and offset. Variant records simply restart the offset at the start of the variant part.

- Functions and procedures: Store number and types of arguments, result type. Some functions, such as `abs ord succ`, may be compiled as in-line code.

- Labels: keep in a separate table if they have a form different from symbols.

- Objects: a `class` in OOP packages together a record of data items and a set of methods, which are procedures associated with the class. In OOP, some form of symbol table for the class is output as well as code for the methods.
Looking up ID in Symbol Table

An identifier that is encountered in executable code must be linked to its appropriate symbol table entries:

TOKEN findid(TOKEN tok) { /* the ID token */
    SYMBOL sym = searchst(tok->stringval);
    tok->symentry = sym;
    SYMBOL typ = sym->datatype;
    tok->symtype = typ;
    if ( typ->kind == BASICTYPE ||
         typ->kind == POINTERSYM)
        tok->basicdt = typ->basicdt;
    return tok;
}
Variable Declarations

A variable declaration has a form such as:

\[
\text{var } \var_1, \var_2, \ldots, \var_n : \text{type} ;
\]

Such a declaration is processed as follows:

1. Find the symbol table entry for \text{type}.

2. For each variable \var_i,

   (a) Allocate storage within the current block using the storage allocation algorithm and the size of \text{type}.

   (b) Make a symbol table entry for the variable, filling in its print name, type, offset, size, and block level.

   (c) Enter the symbol in the symbol table for the current block.
Identifier List etc.

idlist : IDENTIFIER COMMA idlist
        { $$ = cons($1, $3); }
      | IDENTIFIER    { $$ = cons($1, NULL); }
      ;

vblock : VAR vars specs block    { $$ = $3; }
      | block
      ;

vars specs : vargroup SEMICOLON vars specs
            | vargroup SEMICOLON
            ;

vargroup : idlist COLON type
          { instvars($1, $3); }
          ;

type : simple type
      | ... ;

simple type : IDENTIFIER   { $$ = findtype($1); }
           | ... ; /* $1->symtype returns type */

block : BEGIN BEGIN statement endpart
       { $$ = makeprogn($1, cons($2, $3)); }
Data Addressing

A data area is a contiguous region of storage specified by its base address and size.

An item within a data area is specified by the base address of the data area and the offset of the item from the base address.

Two kinds of data areas are arrays and records.

Note that since an item in a data area may itself be a data area, the layout of data in memory may be considered to be a “flattened tree”. A reference to data is a sequence of steps down this tree until the desired data is reached.
Storage Allocation

Allocation of storage is done as an offset to a base address, which is associated with a block of storage. Assignment of storage locations is done sequentially by a simple algorithm:

- Initially, \( \text{next} = 0 \).
- To allocate an item of size \( n \):
  
  
  ```
  \text{offset} = \text{next};
  \text{next} = \text{next} + n;
  \text{return} \ \text{offset};
  ```

- Finally, \( \text{next} \) gives the total size of the block.

In our compiler, the \texttt{next} variable for allocating variables is \texttt{blockoffs[blocknumber]}. 


Alignment and Padding

Certain items must be allocated at restricted locations; e.g., a floating point number must be allocated at a word (4-byte or 8-byte) boundary. This is called storage alignment.

In such cases, next is advanced to the next available boundary if needed, and the intervening storage is wasted; this is called padding.

To pad to a boundary of size $m$, perform:

$$\text{wordaddress}(\text{next}, m) = \left( \frac{\text{next} + m - 1}{m} \right) \times m$$

using truncating integer arithmetic.

For records, a compaction algorithm could be used to minimize wasted storage.
Installing Variables in Symbol Table

/* install variables in symbol table */
void instvars(TOKEN idlist, TOKEN typetok)
{
    SYMBOL sym, typesym; int align;
    typesym = typetok->symtype;
    align = alignsize(typesym);
    while (idlist != NULL) /* for each id */
    {
        sym = insertsym(idlist->stringval);
        sym->kind = VARSYM;
        sym->offset = /* "next" */
            wordaddress(blockoffs[blocknumber],
                align);
        sym->size = typesym->size;
        blockoffs[blocknumber] = /* "next" */
            sym->offset + sym->size;
        sym->datatype = typesym;
        sym->basicdt = typesym->basicdt;
        idlist = idlist->link;
    }
}

blockoffs[blocknumber] is the offset in the current block; this is the next value for this storage allocation.
Record Declarations

A record declaration has a form such as:

\texttt{record } field_1, \ldots, field_n : type_1 \ldots \texttt{ end}

Such a declaration is processed as follows:

1. Initialize offset within the record, \texttt{next = 0}.

2. For each entry group,
   
   (a) Find the symbol table entry for the \texttt{type}.

   (b) Allocate storage within the record using the storage allocation algorithm and size of \texttt{type}.

   (c) Make a symbol table entry for each field, using \texttt{makesym()}, filling in its print name, type, offset in the record, and size.

   (d) Link the entries for the fields to an entry for the record.

3. The size of the record is the total size given by the storage allocation algorithm, rounded up to whole words, e.g. multiple of 16.

4. Variant records simply restart the storage allocation at the place where the variant part begins. Total size is the maximum size of the variants.
Symbol Table Structures for Record

type complex = record re, im: real end;

var c: complex;
Array Declarations

A simple array declaration has a form such as:

\[
\text{array } [ \text{low}_1..\text{high}_1 ] \text{ of } \text{type}
\]

Such a declaration is processed as follows:

1. Find the symbol table entry for \text{type}.
2. Make a symbol table entry for the array type. The total size of the array is:
   \[(\text{high}_1 - \text{low}_1 + 1) \times \text{size(type)}\]

Multiply dimensioned arrays can be treated as arrays of arrays, in the order specified for the language. In Pascal, \text{array}[a..b,c..d] of \text{T} is equivalent to \text{array}[a..b] of \text{array}[c..d] of \text{T}.
Symbol Table Structures for Array

var x: array[1..10] of real;

var z: array[1..5] of array[1..10] of real;

var z: array[1..5, 1..10] of real;
Type Checking, Coercion, and Inference

When a binary operator is reduced, as in our binop program, it is necessary to check the types of the arguments, possibly to coerce an argument to the correct type, and to infer the result type.

Suppose that \( X \) is \texttt{real} and \( I \) is \texttt{integer}.

<table>
<thead>
<tr>
<th>Op</th>
<th>Arg1</th>
<th>Arg2</th>
<th>Op</th>
<th>New Arg1</th>
<th>New Arg2</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>( X )</td>
<td>( X )</td>
<td>+</td>
<td>( X )</td>
<td>( X )</td>
<td>\texttt{real}</td>
</tr>
<tr>
<td>+</td>
<td>( I )</td>
<td>( I )</td>
<td>+</td>
<td>( I )</td>
<td>( I )</td>
<td>\texttt{integer}</td>
</tr>
<tr>
<td>+</td>
<td>( I )</td>
<td>( X )</td>
<td>+</td>
<td>(float ( I ))</td>
<td>( X )</td>
<td>\texttt{real}</td>
</tr>
<tr>
<td>:=</td>
<td>( I )</td>
<td>( X )</td>
<td>:=</td>
<td>( I )</td>
<td>(fix ( X ))</td>
<td>\texttt{integer}</td>
</tr>
<tr>
<td>&lt;</td>
<td>( I )</td>
<td>( X )</td>
<td>&lt;</td>
<td>(float ( I ))</td>
<td>( X )</td>
<td>\texttt{boolean}</td>
</tr>
</tbody>
</table>

- For most operators, the “higher” type takes precedence. Numeric types may be organized in a \textit{type lattice} where e.g. \texttt{char} < \texttt{int} < \texttt{float} < \texttt{double}.
- For assignment, the type of the left-hand side takes precedence.
- The result type is generally the operand type, but is always \texttt{boolean} for relational operators.

The result type is stored in the operator token.
Structure References

References to parts of structures within program code are not hard to handle. The basic principles are:

- Every expression has a type (symtype).
- Types form a tree structure (a graph when pointers to types are included, but still treated as a tree).
- The structure references in source code specify a traversal down the type tree.
- A reference to a part of a structure depends on the type of the structure; the results of the reference are:
  - An address expression for the substructure.
  - A new type for the substructure.

\[(\text{code}, \text{type}) \rightarrow (\text{code}', \text{type}')\]

Repeated application of this procedure handles even complicated references.

There are several basic cases: arrays, records, and pointers.
Structure References....

1. **Arrays:** The address is the base address of the array plus the offset given by the array formula. 

   \[
   \text{(AREF base offset )}
   \]

   The type is the array element type.

2. **Records:** The address is the base address of the record plus the offset of the field within the record: 

   \[
   \text{(AREF base offset )}
   \]

   The type is the field type.

3. **Pointers:** The address is given by accessing the value of the pointer: \( (^ \text{pointer} ) \)

   The type is the type pointed to. This is called dereferencing the pointer.

Because structure references generate many additive constants, it is an important and easy optimization to keep additive constants at the front of the addressing expression and to combine (fold) additive constants as structure accesses are processed:

\[
\text{Address} = \text{BaseAddress} + \sum_{i=1}^{n} \text{Offset}_i
\]
Record References

A record is a data area consisting of a sequence of items, which may be of different sizes and types. Items are addressed by name.

\[
\text{TYPE Z} = \text{RECORD I: INTEGER; X, Y, Z: REAL; VAR W: Z;}
\]

\[
\begin{array}{|c|c|c|}
\hline
\text{Field} & \text{Offset} & \text{Size} \\
\hline
\text{I} & 0 & 4 \\
\text{X} & 8 & 8 \\
\text{Y} & 16 & 8 \\
\text{Z} & 24 & 8 \\
\hline
\end{array}
\]

TOTAL SIZE = 32

\(W.X\) would produce the code \((\text{AREF W 8})\).
Array References

An array is a data area consisting of a linear sequence of items, each of which is of the same size and type. Items are addressed by numeric index.

The address of an array reference must be calculated by the compiler. We assume that the array is declared as:

\[ A : \text{ARRAY[} L_{1..1}, L_{2..2}, \ldots, L_{n..n} \] OF Type \]

The address of a reference \( A[ S_{1}, S_{2}, \ldots, S_{n} ] \) is given by the formula:

\[
\text{Address} = \text{Base}(A) + \sum_{i=1}^{n} (S_{i} - L_{i}) \cdot D_{i}
\]

where for row-major order (C, Pascal),

\[ D_{n} = \text{length of one datum of Type} \]
\[ D_{i-1} = D_{i} \cdot (U_{i} - L_{i} + 1) \]

or for column-major order (Fortran),

\[ D_{1} = \text{length of one datum of Type} \]
\[ D_{i+1} = D_{i} \cdot (U_{i} - L_{i} + 1) \]
Array References in Pascal

Pascal uses *row-major order*, making array declarations and references easy to process.

For array declarations,

\[
\text{array}[i..j, k..l] \text{ of } type
\]

is equivalent to:

\[
\text{array}[i..j] \text{ of array}[k..l] \text{ of } type
\]

These declarations are reduced starting at the right, so that each reduction is of the form:

\[
\text{array}[...] \text{ of } type
\]

where *type* has been completely processed and has a known size.

For array references,

\[a[i,j]\]

is equivalent to:

\[a[i][j]\]

These references are processed left-to-right, so that \[a[i]\] is done first, yielding code for \[a[i]\] and a type that is an array type; then \[j\] is processed relative to that array type.

Using these conventions, arrays with multiple dimensions are handled in the same way as singly-dimensioned arrays.
Does Array Order Matter?

static double arr[1000][1000];

double test1 ()
{
  double sum; int i, j;
  sum = 0.0;
  for (i=0; i<1000; i++)
    for (j=0; j<1000; j++) /* inner loop j */
      sum = sum + arr[i][j]; /* is rightmost [j] */
  return (sum);
}

double test2 ()
{
  double sum; int i, j;
  sum = 0.0;
  for (j=0; j<1000; j++)
    for (i=0; i<1000; i++)
      sum = sum + arr[i][j];
  return (sum);
}

The two programs compute the same result, but performance is quite different:

test1 result = 1000000.0  time = 430000

test2 result = 1000000.0  time = 1940000
Example of Structure Declaration

type date = record  
  mo : 1..12;  
  day : 1..31;  
  year : integer end;

  person = record  
  name : alfa;  
  ss : integer;  
  birth : date end;

var people : array[1..100] of person;

From these declarations, the following symbol table information might be derived:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Offset</th>
<th>Size</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>date</td>
<td>0</td>
<td>16</td>
<td>Link to fields</td>
</tr>
<tr>
<td>mo</td>
<td>0</td>
<td>4</td>
<td>1..12</td>
</tr>
<tr>
<td>day</td>
<td>4</td>
<td>4</td>
<td>1..31</td>
</tr>
<tr>
<td>year</td>
<td>8</td>
<td>4</td>
<td>integer</td>
</tr>
<tr>
<td>person</td>
<td>0</td>
<td>32</td>
<td>Link to fields</td>
</tr>
<tr>
<td>name</td>
<td>0</td>
<td>8</td>
<td>alfa</td>
</tr>
<tr>
<td>ss</td>
<td>8</td>
<td>4</td>
<td>integer</td>
</tr>
<tr>
<td>birth</td>
<td>16</td>
<td>16</td>
<td>date</td>
</tr>
<tr>
<td>people</td>
<td>0</td>
<td>3200</td>
<td>person</td>
</tr>
</tbody>
</table>
Example of Structure Reference

Given the preceding declarations, the reference

```plaintext
people[i].birth.day
```

would be processed as follows:

<table>
<thead>
<tr>
<th>Reference</th>
<th>Expression</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>people[i]</td>
<td>aref(people, (i-1)*32)</td>
<td>person</td>
</tr>
<tr>
<td></td>
<td>= aref(people, -32 + i*32)</td>
<td></td>
</tr>
<tr>
<td>.birth</td>
<td>aref(people, (i-1)*32+16)</td>
<td>date</td>
</tr>
<tr>
<td></td>
<td>= aref(people, -16 + i*32)</td>
<td></td>
</tr>
<tr>
<td>.day</td>
<td>aref(people, (i-1)*32+16+4)</td>
<td>1..31</td>
</tr>
<tr>
<td></td>
<td>= aref(people, -12 + i*32)</td>
<td></td>
</tr>
</tbody>
</table>

It is useful to think of structure descriptions in nested Lisp-like form. For example, the preceding declarations would yield the following type for the array `people`:

```plaintext
(ARRAY (.. 1 100)
  (RECORD (NAME ALFA)
    (SS INTEGER)
    (BIRTH (RECORD
      (MO (.. 1 12))
      (DAY (.. 1 31))
      (YEAR INTEGER))))
)
```

149
An example of a pointer declaration is:

```plaintext
var p: ^person
```

Note that the POINTERSYM record points to the name of the record rather than to the RECORDSYM entry.

A pointer reference such as:

```plaintext
p^.friend
```

is handled like an array reference, with the pointer reference in the base address location:

```plaintext
(aref (^ p) 4)
```

where we assume that 4 is the offset of the friend field from the start of the person record.

The file `pasrec.sample` contains examples of code that is compiled for pointer references.
Types as Tree Structures

Types can be thought of as tree structures:

- Leaf nodes are basic types (integer, real).
- Interior nodes are type constructors (array, record, pointer).

A type declaration builds an interior node from leaf nodes or subtrees.

A structure reference specifies a path through the tree from root to leaf node.

Pointers provide “back arcs” in the tree.
Dynamic Type Checking

Dynamic type checking, used in Lisp, checks types at runtime before operations are performed on data.

- Types are associated with *values*. Requires the ability to determine the type of any data at runtime, e.g. by storing a type *tag* with data. Or, pages of memory can be allocated to specific types; the type of data can be looked up in a table indexed by page address.

- Slower at runtime due to repeated type checking.

- More flexible: union types can be supported, as in the *copy-tree* function.

\[
\text{(defun copy-tree (x)} \\
\text{  (if (consp x)} \\
\text{    (cons (copy-tree (first x))} \\
\text{      (copy-tree (rest x)))} \\
\text{     x))}
\]

Common Lisp combines dynamic type checking with optional type declarations to allow compilation of code using static checks.
Static Type Checking

Static type associates type with *variables*; checking is done once, at compile time.

- The compiler must be able to determine “all” types at compile time: type declarations required.
- Faster at runtime: no type checks, only operations.
- Less error-prone: compile-time type checking.
- Inflexible. Pascal originally included array bounds as part of the type, making it impossible to write general subroutines such as matrix inversion.
Strong Typing

A *sound* type system guarantees that no type errors can occur at runtime. A language with such a system is called *strongly typed*. However,

- Some checks can only be done dynamically, e.g. array bounds checking.
- Such checking can cause serious performance degradation (factor of 2).
- Even so-called strongly typed languages often have “holes” in the type system, e.g. variant records in Pascal.
Type Equivalence

If types are required to match, the question of what types are considered to be “equivalent” arises.

*Structural equivalence* requires equivalent structures (tree equivalence, as in the Lisp function `equal`), i.e.,

- Identical basic types, or
- Same type constructor applied to equivalent types.

However, there is still a question as to what things are included when testing equivalence, e.g., array bounds and record field names. Implementations of the “same” language may vary.

*Name equivalence* considers types to be equal only if the same names are used.

C uses structural equivalence except for records, for which name equivalence is used.
Type Signatures

The signature of a procedure is a description of the types of its arguments (in order) and the type of its result. Often a signature is written in Cartesian product form:

\[
\text{sqrt} : \text{real} \rightarrow \text{real} \\
\text{mod} : \text{integer} \times \text{integer} \rightarrow \text{integer}
\]

Procedure signatures must be put in the symbol table when compiling languages that require type-checking of procedure arguments.

In languages such as Ada, which allow separate compilation of procedures but require argument type checking, type signatures must be part of the output file so that type checking of procedure calls can be performed by the link editor.
Polymorphic Procedures

A procedure that has multiple type signatures is called *polymorphic*. In the case of operators, the use of the same operator with different types is called *overloading*.

\[ + : \text{integer} \times \text{integer} \rightarrow \text{integer} \]
\[ + : \text{real} \times \text{real} \rightarrow \text{real} \]

Polymorphic procedures are often found in object-oriented programming:

```lisp
(defmethod move-to ((self drawable) (x integer) (y integer))
  (send self 'erase)
  (send self 'set-pos x y)
  (send self 'draw)
)
```
Table for Labels

Pascal requires a label statement to pre-declare statement labels:

\texttt{label 1492, 1776;}

It is necessary to ensure that user labels do not conflict with compiler-generated labels. An easy way to do that is to keep user labels in a linear table, whose index becomes the internal label.

Labels used in statements are converted to the internal labels. The intermediate code has both \texttt{label} and \texttt{goto} as operators, each taking an integer internal label number as argument.

\begin{verbatim}
labels[labelnumber++] = tok->intval;

1776: (label 1) goto 1776; (goto 1)
\end{verbatim}
Intermediate Code

Intermediate code is:

• the output of the Parser and the input to the Code Generator.

• relatively machine-independent: allows the compiler to be *retargeted*.

• relatively easy to manipulate (optimize).

Kinds of Intermediate Code

1. Trees
2. Quadruples
3. Triples
4. Polish
5. Assembly Language
6. Machine Language
Trees

Trees are not commonly used as intermediate code, but in my opinion trees are the best:

- Trees are easy to manipulate, optimize, partially evaluate.
- Trees can be transformed using patterns.
- Trees are easily converted to other forms of intermediate code.

The only disadvantage of trees is that they may take more storage; but modern computers have plenty of storage for compilation.
Quadruples

A *quadruple* is a “mini assignment statement” with at most one operator. \( X := A + B * C \) can be represented as:

\[
\begin{align*}
T1 & := B * C \\
T2 & := A + T1 \\
X & := T2
\end{align*}
\]

The four components of a quadruple are:

1. Result
2. Operand 1
3. Operation
4. Operand 2

This is sometimes called *three-address code* since each quadruple involves three variables.

**Advantages:**

1. Flat: can be written to a linear file.
2. Easy to generate (rather poor) code.
3. Can perform peephole optimization.
Triples

A *triple* or *triad* is like a quadruple in which the result component is implicitly given by the triple number. \(X := A + B \times C\) might be represented as:

\[
\begin{align*}
(0) & \quad B \times C \\
(1) & \quad A + (0) \\
(2) & \quad X := (1)
\end{align*}
\]

The three components of a triple are:

1. Operand 1
2. Operation
3. Operand 2
Reverse Polish Notation

Reverse Polish Notation (RPN) is an unambiguous, parenthesis-free notation for arithmetic expressions. Operands precede the operators that apply to them:

$A + (B \times C) \quad \longrightarrow \quad A \ B \ C \ * \ +$

$(A + B) \times C \quad \longrightarrow \quad A \ B \ + \ C \ *$

It is easy to produce RPN as output of an operator precedence parser:

1. Operands go directly to the output; no operand stack is used.
2. When an operator is reduced, it is removed from the operator stack and put into the output.

---

32The description "Polish" refers to the nationality of logician Jan Łukasiewicz, who invented (prefix) Polish notation in the 1920s. – Wikipedia
Trees and Reverse Polish

It is easy to convert a tree representation to RPN by a postorder recursive algorithm:

1. If the expression to be converted is an operand (leaf node), put it into the output.

2. Otherwise, the expression is a subtree. Convert the left-hand operand, then convert the right-hand operand, then put the operator into the output.
Converting a Tree to RPN

(defun tree-to-polish (exp)
  (nreverse (tree-to-p exp nil)))

(defun tree-to-p (exp result)
  (if (atom exp) ; if leaf
      (cons exp result) ; push
      (progn
        (mapc #'(lambda (opnd) ; operands
                 (setq result
                       (tree-to-p opnd
                                  result)))
               (rest exp))
        (cons (first exp) result))))) ; add op

(tree-to-polish '(+ (* a b) c)) = (A B * C +)

(setq testx '(/ (+ (minus b)
                (sqrt (- (expt b 2)
                         (* 4 (* a c))))))
       (* 2 a)))

(tree-to-polish testx)
  = (B MINUS B 2 EXPT 4 A C * * - SQRT + 2 A * /)
RPN is easily executed by a stack machine:

1. Operands are pushed onto the stack.

2. When an operator is encountered, the appropriate number of operands is popped from the stack and the operator is applied to them. The result is pushed onto the stack.

3. When the end of the input expression is reached, the result is the top of the stack.

HP makes a line of pocket calculators that use RPN.
Executing RPN

(defvar execute-rpn (rpn)
  (let (stack rhs)
    (dolist (item rpn)
      (if (numberp item)
        (push item stack)
        (progn (setq rhs (pop stack))
          (push (if (unaryp item)
            (funcall item rhs)
            (funcall item
              (pop stack)
              rhs))
            stack))))
    (pop stack))
    (defun unaryp (x) (member x '(minus sqrt)))))

(execute-rpn '(3 4 + 5 *)) = 35

(execute-rpn (sublis '((a . 1)
                         (b . -3)
                         (c . 2))
                         (tree-to-polish testx)))
  = 2.0
RPN as Intermediate Code

An entire program can be expressed in Reverse Polish intermediate code. For example, by reading the pretty-printed intermediate code from `graph1.pas` into Lisp and converting it to RPN, the following is obtained:

```plaintext
(I 0 := 1 LABEL I 32 <= X 0.0625 I FLOAT * :=
Y EXP X - FUNCALL SIN 6.28318 X * FUNCALL * :=
N ROUND 32.0 Y * FUNCALL 34 + := 0 LABEL
WRITE " " FUNCALL N N 1 - := N 0 = PROGN
0 GOTO IF PROGN WRITELN "*" FUNCALL
I I 1 + := 1 GOTO PROGN IF PROGN)
```

It must be clear how many operands each operator takes, so a construct such as `progn` must be replaced by `prog2`, `prog3`, etc.
The Code Generator is the final stage of the compiler. It accepts intermediate code from the Parser and produces machine code for a particular target machine.

Output code may be:

- *Absolute code* with fixed memory addresses, either to a file (executable or `.exe`) or directly into memory.
- *Relocatable code* that can be converted to run at different places in memory; this is done by the *link editor* or *linker*. 
Loading Process

An absolute file is loaded and executed by the loader (part of the operating system) with the following conceptual steps:

1. Allocate memory for each program segment.
2. Read the memory image into main memory from the absolute file on disk.
3. Set the base register to the initial address of the segment and set the bounds register to the size of the segment.
4. Jump to the starting address of the program, using a special jump instruction that switches the processor state from system mode to user mode during the jump.
Absolute File

An absolute file or executable is a file of program code and data that is ready for loading and execution. It is absolute in the sense that every address is an absolute (numeric) address.

An absolute file consists of:

- A size and starting address
- A memory image for the code segment, and perhaps a memory image for the data segment.
- A list of BSS (Block of memory Starting with Symbol) elements:
  - Starting address
  - Size
  - Initial data value
Initializing BSS Storage

A block of data can be declared in assembly language with a **BSS** (Block Starting with Symbol) pseudo-op:

```assembly
bigarray:  bss    8000000
```

Similar data can be declared in high-level languages:

```c
double bigarray[1000][1000];
```

Instead of representing such a large block as a memory image, the block is represented in the absolute file by giving its starting address, size, and the initial value. The loader will fill the memory area with the initial value.

Although the loader might not have to initialize **BSS** areas, there are several advantages to doing so:

- It prevents security problems: otherwise, a program can see the previous program’s data.
- It makes a program run the same way each time. Otherwise, a program might work if the initial value is lucky, but not work for other values.
- It allows detection of use of uninitialized data if the array is filled with the **SNaN** (Signaling Not a Number) value.
Banked Memory

A *load* instruction transfers data from memory to a register; a *store* instruction transfers data from a register to memory.

Some CPU architectures employ a *banked memory* in which memory is divided into two *banks* that can be accessed independently. This allows instruction fetching (from the instruction bank) to be overlapped with data access (from the data bank).

\[ \text{I1: LDA } X \quad y := x \]
\[ \text{I2: STA } Y \]

With banked memory, the CPU can run twice as fast. On such a machine, the compiler and linker will have to put code and data in separate banks.
Location Counter

As code is generated, it will be put into the next available location in a static data area. A location counter keeps track of the next available location in the data area.

1. Initially, the LC is set to 0.
2. After each instruction is generated, the LC is incremented by the length of the instruction.
3. When a label is encountered, the relative address of the label is set to the value of the LC.
4. At the end, the length of the code segment is the value of the LC.

There may be multiple location counters, e.g., one for code and one for static data.
Example of Assembly Listing

1 0000 #9
2 0000   global _GRAPH1
3 0000   _GRAPH1:
4 0000 480E FFFF FFE8 link.l %a6,&LF1
5 0006 48D7 0000 movm.l &LS1,(%sp)
6 000A F236 F000 0170 FFFF fmovm.x &LSF1,LFF1(%a6)
   FFE8
7 0014 7000 movq.l &0,%d0
8 0016 2D40 FFF8 mov.l %d0,-8(%a6)
9 001A L1:  
10 001A 202E FFF8 mov.l -8(%a6),%d0
11 001E 7220 movq.l &32,%d1
12 0020 B280 cmp.l %d1,%d0
13 0022 6DFF 0000 00A2 blt.l L3
14 0028 F239 5400 0000 00CC fmov.d L4,%fp0
15 0030 F200 4080 fmov.l %d0,%fp1
16 0034 F200 0423 fmul %fp1,%fp0
17 0038 F22E 7400 FFE8 fmov.d %fp0,-24(%a6)
18 003E F200 001A fneg %fp0
19 0042 F200 0010 fetox %fp0
20 0046 F239 5480 0000 00D4 fmov.d L5,%fp1
21 004E F22E 5500 FFE8 fmov.d -24(%a6),%fp2
22 0054 F200 08A3 fmul %fp2,%fp1
   ...
50 00BC 2D40 FFF8 mov.l %d0,-8(%a6)
51 00C0 60FF FFFF FF58 bra.l L1
52 00C6 L3:  
53 00C6 4E5E unlk %a6
54 00C8 4E75 rts
55 00CA   set LF1,-24
56 00CA   set LS1,0
57 00CA   set LFF1,-24
58 00CA   set LSF1,0
59 00CC   data
60 00CC   lalign 4
61 00CC 3FB0 0000 0000 0000 L4:  long 0x3fb00000,0x0 # 6.25e-02
62 00D4 4019 21FA 0000 0000 L5:  long 0x401921fa,0x0
63 00DC 4040 0000 0000 0000 L6:  long 0x40400000,0x0
64 00E4 2000 L7:  byte 32,0
65 00E6 2A00 L8:  byte 42,0
66 00E8 version 2
Backpatching

In order to compile code for jump (goto or branch) instructions, it is necessary to know the address in memory (relative to the location counter) of the destination of the branch. Branch instructions may be PC-relative or have absolute addresses. For forward branches the destination address will not be known when the branch is encountered. There are two approaches to this problem:

1. Two passes. The first pass through the code generator computes addresses but does not generate code. The second pass generates code and uses the addresses determined in the first pass. This approach takes longer.

2. Backpatching. The generated code itself is used to hold a linked list of places where forward reference addresses are needed. When the address is found, it is patched back into the generated code.
Linker

The link editor or linker combines one or more relocatable or object files with libraries, such as the math library and I/O library, to form an absolute file or executable.\textsuperscript{33}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{linker_diagram.png}
\caption{Diagram of the linker process.}
\end{figure}

\textsuperscript{33}Diagram from Wikipedia.
Linking Process

The task of the linker is to convert a set of relocatable files into an absolute file that can be executed. The link editor is called ld in Unix; it is called automatically by compilers in most cases.

Linking involves several steps:

1. Determine the relocatable code modules that are needed.

2. Allocate memory and assign absolute addresses for each module.

3. Determine absolute addresses of external symbols.

4. Relocate the code to produce an absolute code file.
Relocatable Code

A relocatable code file contains the following items:

1. Size of each static data area; each data area corresponds to a *location counter*. There may be one data area, two for code and for data, or many.

<table>
<thead>
<tr>
<th>LC</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>1</td>
<td>400</td>
</tr>
</tbody>
</table>

2. Table of *imported symbols*: external symbols (not defined in that module) that are referenced by the code.

<table>
<thead>
<tr>
<th>N</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>SIN</td>
</tr>
<tr>
<td>1</td>
<td>EXP</td>
</tr>
</tbody>
</table>

3. Table of *exported symbols* or entry points; for each, its location counter number and offset from that location counter.

<table>
<thead>
<tr>
<th>Name</th>
<th>LC</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRAPH1</td>
<td>0</td>
<td>40</td>
</tr>
</tbody>
</table>

4. Data or code for each data area.
Finding Relocatable Modules

The linker is given the name of one or more program modules that should be included. These form the initial module set.

```plaintext
cc driver.c graph1.s -lm
```

1. For each module, the exported symbols and imported symbols are collected.

2. If there is some imported symbol that it not defined, it is necessary to find a relocatable module that defines it. This is done by searching through one or more libraries, which are collections of relocatable files. This process typically occurs for system library routines such as `sin` or `writeln`.

3. The above processes are repeated until no undefined symbols remain. If a symbol cannot be found, an `unsatisfied external reference` error is reported.

4. If any external symbol is defined more than once, a `multiply defined external symbol` error is reported.
Assigning Absolute Addresses

Absolute addresses are assigned using the storage allocation algorithm for each module. If the CPU has a banked memory, the instruction and data segments will be allocated in separate banks.

Suppose that the set of relocatable modules to be loaded is A, B, and C, with sizes and addresses as shown below:
Absolute Addresses

Once absolute addresses have been assigned to each storage block (location counter) of each module, the absolute address of each entry point can be determined.
Linker

At this point, the linker has constructed a set of tables:

1. An absolute memory address for each data area. This address is used to relocate references to data in this area.

<table>
<thead>
<tr>
<th>File</th>
<th>LC</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>0000</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>1000</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>0300</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>1200</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0500</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>1600</td>
</tr>
</tbody>
</table>

2. External symbols and their addresses:

<table>
<thead>
<tr>
<th>Name</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIN</td>
<td>0024</td>
</tr>
<tr>
<td>GRAPH1</td>
<td>0340</td>
</tr>
<tr>
<td>SIN</td>
<td>0520</td>
</tr>
<tr>
<td>EXP</td>
<td>0620</td>
</tr>
</tbody>
</table>

The next step is to convert the code and data to absolute form.
Form of Relocatable Code

Program code consists of instructions; each instruction may have an address field that contains the *offset* of a variable or label from its data area. In addition, the instruction will have a relocation bit or field that indicates whether the address should be relocated. If the relocation bit is set, the corresponding location counter is added to the address.

\[ \text{OP} | \text{Rel. Address} | R | \text{LC} | \rightarrow | \text{OP} | \text{Abs. Address} \]

R is a relocation code; it could be:

1. Do not modify the word.
2. Relocate the address field by adding the value of location counter \text{LC} to it.
3. Replace the address field by the address of the external symbol whose number is given in the address field.

Relocatable code may contain other kinds of code items, *e.g.*, \text{BSS} codes to specify blocks to be filled with a specified value such as 0.
Dynamically Linked Library

A dynamically linked library (DLL) is not part of an absolute file, but is linked in at load time or runtime. The primary motivation of a DLL is to allow multiple programs to share a single copy of a large library, such as X Windows. DLLs also allow a library update (e.g. security patch) to be effective for all programs without re-linking.

Ways to link in the DLL include:

- Let the loader do the linking at load time. The absolute file contains information on what external symbols are needed and where they go.
- Let the program make calls to initialize itself on first call.
- Leave the calls undefined, so that they generate error traps at runtime. The OS figures out what the calls should be and fixes the code at the point of call.
Position Independent Code

Position independent code (PIC) or a position independent executable (PIE) is code that can run correctly at an arbitrary memory location.

Ordinary absolute code specifies a full absolute address for operands, so that the code will not work if moved to another location in memory:

100240: load pi --> LOAD 100260

...  
100260: pi: 3.1415

Position independent code uses an address relative to the current instruction pointer (IP) or program counter (PC):

100240: load pi(rip) --> LOAD 20 (rip)

...  
100260: pi: 3.1415

This code would work if moved to another location. The address field is also smaller, which might save memory and make it faster.
Advantages of Position Independent Code

When code is position independent, the same shared library can be used by multiple programs, appearing to be at a different virtual memory address in each while remaining at a single physical address.

Position independent code also allows the OS to randomize the addresses of library modules, preventing certain kinds of security attacks.
Run-Time Support

Run-time support includes:

1. Library routines (math functions, I/O formatting)
2. Interface with operating system (I/O, termination)
3. Memory management (new, garbage collection)
4. Debugging support
Operations by Subroutine

Functions may be specified in source code either as operators or as function calls; the compiler may generate either form as instructions or as a subroutine call.

A function can be compiled *inline* if the code is short:

\[ \text{abs}(x) \rightarrow (\text{if } (\geq x 0) x (-x)) \]

or the code generator can generate a special instruction sequence, e.g. to float an integer.

An operator can be compiled as a subroutine call if the operation does not exist as a machine instruction.

\[ x^{y} \rightarrow \text{qq8rtor}(x,y) \]

\texttt{cout} \texttt{<< "Hello\n"}

On small machines without floating point hardware, all floating ops may be done by subroutine calls.
Special Subroutines

In C, `printf` is an ordinary subroutine.

However, in Pascal, `write` cannot be just an ordinary subroutine because `write` must know the types of its arguments in order to convert them correctly. This can be done in two ways:

- The compiler can add a type argument to the call to the library routine:
  \[ \text{write}(x) \rightarrow \text{write}(x, \text{REAL}) \]

- The compiler can call different library routines depending on the argument type:
  \[ \text{write}(x) \rightarrow \text{writef}(x) \]

We will assume the second convention for our assignments; we will use `write` and `writeln` for strings, `writei` and `writeln` for integers, and `writef` and `writelnf` for floats.
Memory Management

Many languages can allocate *heap* storage at runtime.

```pascal
type person = record ... end;
var p: ^person;

... new(p);
```

The compiler must insert the size of the `person` record into the call to `new`. If type safety is to be guaranteed, it may be necessary to initialize the new record.

For our assignments, we will assume the following conversion:

```
new(p) → p := new(sizeof(p^))
```

For example, source code `new(p)` would be converted to intermediate code `(:= p (funcall new 40))`, where `40` is the size of the record type `p` points to.

Pascal uses the form `new(p)` and prohibits expressions involving pointers in order to prohibit pointer arithmetic (which destroys type safety). C allows pointer arithmetic; in C, `malloc` is called with the record size as a parameter, and a type cast is used to set the result type.
Returning Memory

Some languages allow requested storage to be freed or returned to the heap. This is an efficient method of storage management, but it allows two kinds of errors:

- Forgetting to return memory: a storage leak.
- Returning the same memory more than once. This can produce errors that are very difficult to find.

Released storage can be held in linked lists that are pointed to by an array of pointers, where the array is indexed by block size.

Potential problem: mismatch of block sizes. The user requests and releases many blocks of size 7, then needs blocks of size 5.

Larger blocks can be subdivided, but this leads to fragmentation (many small blocks that cannot be used). The buddy system (see Knuth) is one way of combining smaller blocks into larger ones when possible.

malloc puts the size of a block behind the block (just before the pointer value that is returned). This makes it easy to check whether adjacent blocks have been returned, so that they can be combined. However, a misbehaving program can overwrite the size and crash the system.
Heap Memory Management

void * new(size)
long size;
{ CONS * tmp;
    if ( free[size] )
    { tmp = (CONS *) free[size];
        free[size] = tmp->car;
        return (tmp); }
    else if ( (void *) ( (int) nextfree + size) < maxfree )
    { tmp = nextfree;
        nextfree = (void *)
                ( (int) nextfree + size);
        return (tmp); }
    else error("Out of Memory");
}

release(block, size)
void * block; long size;
{ ((CONS *) block)->car = free[size];
    free[size] = block;
}
Garbage Collection

Garbage collection is a method of automatically recycling storage that is no longer in use:

- If heap storage is available, return the next item of heap storage.
- Otherwise, perform a garbage collection to reclaim unused storage. If enough was collected, allocate the requested item and continue.
- Otherwise, request more memory from the operating system.
- Otherwise, fail due to lack of memory.

Garbage collection requires that the type of every piece of runtime memory be identifiable by the garbage collector, and that there are no possible errors in type determination. This may difficult for some languages, especially if the language allows variant records or pointer arithmetic. Garbage collection has been used in Lisp since about 1960; it is also used in Java.
Garbage Collection

*Garbage collection* identifies the cells of memory that are in use; the remaining cells, which are not used for anything, are collected and added to the Free List. This automatic recycling of unused memory is a major advantage of Lisp; it makes it possible for programs to create ("cons up") new structures at will without having to worry about explicitly returning unused storage.

Identification of “in use” memory starts from symbols, which are always “in use”. Symbols, in turn, may have several pointers to other data structures:

1. Binding (value) of the symbol.
2. Function Definition.
3. Property List.

Each of these structures, if present, must also be marked as being “in use”.

195
Mark-And-Sweep Garbage Collection

Mark-and-sweep garbage collection first marks all storage cells that are in use, then sweeps up all unmarked cells. Symbol cells are marked, and all pointers from the symbols are followed using the following recursive algorithm:

1. If the pointer points to a Symbol or to a marked cell, do nothing.

2. Otherwise (pointer points to a cons Cell),
   (a) Mark the cell itself.
   (b) Apply the marking algorithm to the first of the cell.
   (c) Apply the marking algorithm to the rest of the cell.
Mark-and-Sweep ...

After all cells that are in use have been marked, the Sweep phase is run. All memory cells are examined, in order of increasing address. Those cells that are not marked are pushed onto the Free List.

“Marking” a cell may use an available bit within the cell, or it may use a separate bit table that uses one bit to represent each word.

Mark-and-Sweep garbage collection is conceptually simple. However, it requires time that is proportional to the total size of the address space, independent of how much garbage is collected. This is a disadvantage for large address spaces.

Another disadvantage of this algorithm is that all computation stops for several seconds while garbage is collected. This is not good for real-time applications, e.g., a robot walking down stairs.
Copying Garbage Collection

Another method of garbage collection is to divide the total address space of the machine into two halves. When storage is exhausted in one half, garbage collection occurs by copying all storage that is in use to the other half. Unused storage, by definition, doesn’t get copied.

A copying collector uses time proportional to the amount of storage that is in use, rather than proportional to the address space. This is advantageous for programs that generate lots of garbage. Copying also tends to put list structures in nearby addresses, improving memory locality.

A copying collector has two disadvantages:

1. Half the address space of the machine may be lost to Lisp use, depending on the implementation.

2. There is a long period during which computation stops for garbage collection.
Reference Counting

Another method of managing Lisp storage involves *reference counting*. Conceptually, within each cons cell there is room for a small counter that counts the number of pointers which point to that cell. Each time another pointer to the cell is constructed, the counter is incremented by one. Each time a pointer is moved away from the cell, the counter is decremented by one.

Whenever the reference count of a cell becomes zero, the cell is garbage and may be added to the Free List. In addition, the reference counts of whatever *its* pointers point to must also be decremented, possibly resulting in additional garbage.
Reference Counting...

Advantages:

1. Garbage collection can be *incremental*, rather than being done all at once. Garbage collection can occur in short pauses at frequent time intervals, rather than in one long pause.

2. Time spent in collection is proportional to *amount collected* rather than to *address space*.

Disadvantages:

1. More complexity in system functions (*cons*, *setq*, *rplaca*, etc.).

2. Requires storage bits within each *cons* cell, or other clever ways of representing counts.

3. Cannot garbage-collect circular structures (since reference count never becomes zero).
Garbage Collection Is Expensive

Garbage collection is safer and more convenient for the programmer than explicit releasing of storage.

However, whatever the implementation, garbage collection is usually computationally expensive. As a rough rule of thumb, one can think of a cons as taking 100 times as much CPU time as a basic instruction.

The moral: avoid unnecessary conses.
Compiled Procedure

<table>
<thead>
<tr>
<th>Prologue</th>
<th>Procedure Code</th>
<th>Epilogue</th>
</tr>
</thead>
</table>

**Prologue:** (or *preamble*) Save registers and return address; transfer parameters.

**Epilogue:** (or *postamble*) Restore registers; transfer returned value; return.

A *return* statement in a procedure is compiled to:

1. Load the returned value into a register.
2. *goto* the Epilogue.
Subroutine Call Is Expensive

The prologue and epilogue associated with each procedure are overhead that is necessary but does not do user computation.

• Even in scientific Fortran, procedure call overhead may account for 20% of execution time.
• Fancier languages have higher procedure call overhead.
• Relative overhead is higher for small procedures.
• Breaking a program into many small procedures increases execution time.
• A GOTO is much faster than a procedure call.
• Modern hardware architecture can help:
  – Parameter transfer
  – Stack addressing
  – Register file pointer moved with subroutine call
Activations and Control Stack

An activation is one execution of a procedure; its lifetime is the period during which the procedure is active, including time spent in its subroutines.

In a recursive language, information about procedure activations is kept on a control stack. An activation record or stack frame corresponds to each activation.

The sequence of procedure calls during execution of a program can be thought of as a tree. The execution of the program is the traversal of this tree, with the control stack holding information about the active branches from the currently executing procedure up to the root.
Environment

The *environment* of a procedure is the complete set of variables it can access; the *state* of the procedure is the set of values of these variables.

A *binding* is an association of a name with a storage location; we use the verb *bind* for the creation of a binding and say a variable is *bound* to a location. An environment provides a set of bindings for all variables.

An assignment, e.g. \( \text{pi} := 3.14 \), changes the state of a procedure but not its environment.
Run-time Memory Organization

[Figure from Wikipedia.]
Code Generation

We assume that the input is error-free and complete, for example that any type conversion operators have already been inserted.\footnote{This slide was written by John Werth.}

Can generate:

- Binary
  - absolute
  - relocatable
- Assembly
- Interpreted code (e.g. Java byte codes)

Problems include:

- Instruction selection
- Register management
- Local optimization
Code Generation

Code generation can be broken into several steps:

1. Generate the prologue
2. Generate the program code
3. Generate the epilogue

Subroutines are provided to generate the prologue and epilogue.

The arguments to the code generator are:

```c
/* code tree stack frame size */
gencode(parseresult, blockoffs[blocknumber],
labelnumber);

parseresult = pointer to code tree:
    (program foo (progn output)
        (progn ...))
blockoffs[blocknumber]
    = size of local variables, bytes
labelnumber = max label number used so far
```
A starter program `codgen.c` is furnished. A very simple program, `triv.pas`, can be compiled by `codgen.c`:

```plaintext
program graph1(output);
var i:integer;
begin   i := 3   end.
```

The result is `triv.s`:

```plaintext
.globl graph1
   .type graph1, @function
graph1:
   ...
   subq $32, %rsp       # space for stack frame
# ----- begin Your code -----
   movl $3,%eax       # 3 -> %eax
   movl %eax,-32(%rbp) # i := %eax
# ----- begin Epilogue code ---
   leave
   ret
```
Running Generated Code

Programs can be run using `driver.c` as the runtime library:

```
% cc driver.c triv.s -lm
% a.out
calling graph1
exit from graph1
```

`driver.c` is quite simple:

```c
void main()
{
    printf("calling graph1\n");
    graph1();
    printf("exit from graph1\n");
}

void write(char str[])
{
    printf("%s", str);
}

void writeln(char str[])
{
    printf("%s\n", str);
}

int iround(double x) ...
```
Overview of Code Generation

We will take a hierarchical approach to code generation:

- **genc(code)** generates code for a statement. There are only a few kinds of statements. **genc** is easy to do given **genarith**.

- **genarith(expr)** generates code for an arithmetic expression. **genarith** is a classical postorder tree-recursive program, with a simple basic form (but many special cases). **genarith** is not hard given **getreg**.

- **getreg(kind)** gets a register from a pool of available registers. It also handles returning unused registers with **unused(reg)**.

- While register management can be complex, a simple implementation of **getreg()** works pretty well. We will discuss some improvements.
The function \texttt{genc(code)} generates code for a statement. There are only a few kinds of statements:

1. \texttt{PROGN}
   
   For each argument statement, generate code.

2. \texttt{:=}
   
   Generate the right-hand side into a register using \texttt{genarith}. Then store the register into the location specified by the left-hand side.

3. \texttt{GOTO}

   Generate a Jump (branch) to the label number.

4. \texttt{LABEL}

   Generate a Label with the label number.

5. \texttt{IF}

   (\texttt{IF c p1 p2}) can be compiled as:

   \texttt{IF c GOTO L1; p2; GOTO L2; L1: p1; L2:}

   Optimizations are discussed later.

6. \texttt{FUNCALL}

   Compile short \textit{intrinsic} functions in-line. For others, generate subroutine calls.
Arithmetic Expressions

Code for arithmetic expressions on a multi-register machine can be generated from trees using a simple postorder recursive algorithm.

The specifications of the recursive algorithm are:

- **Input:** an arithmetic expression tree
- **Side Effect:** outputs instructions to the output file
- **Output:** returns the number of a register that contains the result.
Basic Expression Algorithm

The basic algorithm for expressions is easy: postorder.

- **Operand** (leaf node): get a register; generate a *load*; return the register.

- **Operator** (interior node): generate operand subtrees; generate op; free operand register; return result register.

; given expr x, return register with value
(defun genarith (x)
  (if (atom x) ; if leaf, id/num
      (genload x (getreg)) ; load: mem -> reg
      (genop (op x) ; else op
        (genarith (lhs x)) ; on subtrees
        (genarith (rhs x)) ) )
)

>(genarith ’(* (+ a b) 3))
LOAD A,R1 ; load: memory -> register
LOAD B,R2
ADD R1,R2
LOAD 3,R3
MUL R2,R3
R3
Trace of Expression Algorithm

\[ \text{>(genarith '(* (+ a b) 3))} \]

1> (GENARITH (* (+ A B) 3))

2> (GENARITH (+ A B))

3> (GENARITH A)

4> (GENLOAD A R1)

LOAD A,R1

<4 (GENLOAD R1)

<3 (GENARITH R1)

3> (GENARITH B)

4> (GENLOAD B R2)

LOAD B,R2

<4 (GENLOAD R2)

<3 (GENARITH R2)

3> (GENOP + R1 R2)

ADD R1,R2

<3 (GENOP R2)

<2 (GENARITH R2)

2> (GENARITH 3)

3> (GENLOAD 3 R3)

LOAD 3,R3

<3 (GENLOAD R3)

<2 (GENARITH R3)

2> (GENOP * R2 R3)

MUL R2,R3

<2 (GENOP R3)

<1 (GENARITH R3)

R3
Arithmetic Expression Algorithm

The \textit{genarith} input is a tree (operand or operator):

- **Operand (leaf node):** id or number
  
  1. Get a register of the right kind (integer, real)
  2. An operand may be a variable or constant:
     
     (a) Variable: Generate an instruction to load the variable into the register.
     
     (b) Constant:
        
        i. Small constant: Generate an \textit{immediate} instruction to load it into the register directly.
        
        ii. Otherwise, make a \textit{literal} for the value of the constant. Generate an instruction to load the literal into the register.

  3. Return the register number.

- **Operator (interior node):**
  
  1. Recursively generate code to put each operand into a register.
  2. Generate the operation on these registers, producing a result in one of the source registers.
  3. Mark the other source register unused.
  4. Return the result register number.
Register Management

Issues are:

- register allocation: which variables will reside in registers?
- register assignment: which specific register will a variable be placed in?

Registers may be:

- general purpose (usually means integer)
- float
- special purpose (condition code, processor state)
- paired in various ways (multiply, divide)

---

\[35\] This slide was written by John Werth.
Simple Register Allocation

Note that there may be several classes of registers, *e.g.*, integer data registers, index registers, floating point registers.

A very simple register allocation algorithm is:

1. At the beginning of a statement, mark all registers as not used.

2. When a register is requested,
   
   (a) If there is an unused register, mark it used and return the register number.
   
   (b) Otherwise, punt.\(^{36}\)

On a machine with 8 or more registers, this algorithm will almost always work. However, we need to handle the case of running out of registers.

---

\(^{36}\)E.g., print a message saying that the expression is too complex and needs to be simplified.
Heuristic for Expressions

The likelihood of running out of registers can be reduced by using a heuristic in generating code for expressions:

Generate code for the *most complicated* operand first.

The “most complicated” operand can be found by determining the size of each subtree. However, simply generating code for a subtree that is an operation before a subtree that is a simple operand is usually sufficient.

With this simple heuristic, on a machine with 8 or more registers, the compiler will never\(^\text{37}\) run out.

If a machine allows arithmetic instructions to be used with a full address, the operation may be combined with the last load.

\(^\text{37}\)Well, hardly ever.
Improving Register Allocation

The simple register allocation algorithm can be improved in two ways:

- Handle the case of running out of available registers. This can be done by storing some register into a temporary variable in memory.

- Remember what is contained in registers and reuse it when appropriate. This can save some load instructions.
An improved register allocation algorithm, which handles the case of running out of registers, is:

1. At the beginning of a statement, mark all registers as not used; set use number to 0.

2. When an operand is loaded into a register, record a pointer to its token in the register table.

3. When a register is requested,
   
   (a) If there is an unused register: mark it used, set its use number to the current use number, increment the use number, and return the register number.
   
   (b) Otherwise, find the register with the smallest use number. Get a temporary data cell. Generate a Store instruction (spill code) to save the register contents into the temporary. Change the token to indicate the temporary.

Now, it will be necessary to test whether an operand is a temporary before doing an operation, and if so, to reload it. Note that temporaries must be part of the stack frame.
Example of Code Generation

Expression: \( (A+B)*(C+3) \)

Initially:
- NUSE = 0
- NTEMP = 0
- NODE = a

<table>
<thead>
<tr>
<th>Pointer Used</th>
<th>Use No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>0</td>
</tr>
<tr>
<td>X2</td>
<td>0</td>
</tr>
<tr>
<td>X6</td>
<td>0</td>
</tr>
</tbody>
</table>

1. Operands of \( a \) not in registers. Push down to \( b \).
2. Operands of \( b \) not in registers. Push down to \( y \).
3. \( y \) is a variable. Get a register (X1)
   
   Generate \( SA1 \ Bo+A \)

Now:

<table>
<thead>
<tr>
<th>Pointer Used</th>
<th>Use No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>1</td>
</tr>
<tr>
<td>X2</td>
<td>0</td>
</tr>
<tr>
<td>X6</td>
<td>0</td>
</tr>
</tbody>
</table>

4. Move to next operand (S). Get a register (X2)
   
   Generate \( SA2 \ Bo+B \)

<table>
<thead>
<tr>
<th>Pointer Used</th>
<th>Use No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>1</td>
</tr>
<tr>
<td>X2</td>
<td>1</td>
</tr>
<tr>
<td>X6</td>
<td>0</td>
</tr>
</tbody>
</table>
Example (2)

5. No more operands; pop up to β.
Operands of β are in Registers, so we can generate code.
Assume use of first operand register for Result.

\[
\begin{align*}
\alpha & : * \\
\xrightarrow{\beta} \\
\xrightarrow{\gamma} \\
\xrightarrow{\delta} \\
\xrightarrow{\epsilon} \\
\xrightarrow{\zeta} \\
\xrightarrow{\eta} \\
\end{align*}
\]

\[
\begin{array}{|c|c|c|}
\hline
\text{Pointer} & \text{Used} & \text{Use No.} \\
\hline
\text{x1} & \beta & 1 \quad 3 \\
\text{x2} & 0 & 0 \\
\text{x6} & 0 & 0 \\
\hline
\end{array}
\]

6. Move across to next element at same level (ε).
Its operands are not in registers, so push down to ε.

7. θ is a variable. Get a register (x2).

\[
\begin{align*}
\alpha & : * \\
\xrightarrow{\beta} \\
\xrightarrow{\gamma} \\
\xrightarrow{\delta} \\
\xrightarrow{\epsilon} \\
\xrightarrow{\zeta} \\
\xrightarrow{\eta} \\
\end{align*}
\]

\[
\begin{array}{|c|c|c|}
\hline
\text{Pointer} & \text{Used} & \text{Use No.} \\
\hline
\text{x1} & \beta & 1 \quad 3 \\
\text{x2} & 0 & 0 \\
\text{x6} & 0 & 0 \\
\hline
\end{array}
\]

8. Move across to element at same level (η).
It is a constant. Look up in constant table; assume its offset in constant table is 4.

Get a Register: No loadable register is free.
Select register with smallest use number (x1).
Example (3)

Generate a Store of XL: BX6 X1
SA6 B0T8+0

(The 0 is the current value of NTEMP)

NTEMP = NTEMP + 1
Change node β to a temporary node.

NEVREG = X1

Now we can load the constant 3: |
SA1 B01c8+4

<table>
<thead>
<tr>
<th>Pointer Used</th>
<th>Use No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>1</td>
</tr>
<tr>
<td>X2</td>
<td>3</td>
</tr>
<tr>
<td>X6</td>
<td>0</td>
</tr>
</tbody>
</table>

9. No more operands, pop up to ε.
Operands of ε are in registers, so we can generate code.
Assume first operand register for result.

Generate R×2 Y2+X1
Release Register X1
Release Nodes Y and Y1
Change node ε to Register.

<table>
<thead>
<tr>
<th>Pointer Used</th>
<th>Use No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>0</td>
</tr>
<tr>
<td>X2</td>
<td>ε</td>
</tr>
<tr>
<td>X6</td>
<td>0</td>
</tr>
</tbody>
</table>
Example (4)

10. No more operands at this level. Pop up to Node α.

11. An operand of Node α is not a register. Push Down to β.

12. β is a Temporary. Get a Register (x1)

Generate Load: SA1 BO+T$+t

13. Move to next node at same level (e). It is a register, so no action is taken.

14. No more nodes at this level, so pop up to Node α.

15. Arguments of Node α are Registers, so we generate code.

Generate RX1 X1 = X2
Release Register X2
Release Nodes β and e
Change node α to Register.

16. Top node is a register, so Stop; Result is in X1.
Reusing Register Contents

<table>
<thead>
<tr>
<th>Used</th>
<th>Contents</th>
</tr>
</thead>
</table>

Many instructions can be eliminated by reusing variable values that are already in registers:

1. Initially, set the contents of each register to \texttt{NULL}.
2. When a simple variable is loaded, set the \texttt{contents} of the register to point to its symbol table entry.
3. When a register is requested, if possible choose an unused register that has no contents marked.
4. When a variable is to be loaded, if it is contained in an unused register, just mark the register used. This saves a Load instruction.
5. When a register is changed by an operation, set its contents to \texttt{NULL}.
6. When a value is stored into a variable, set the contents of any register whose contents is that variable to \texttt{NULL}. Then mark the register from which it was stored as containing that variable.
7. When a Label is encountered, set the contents of all registers to \texttt{NULL}.
8. The \textit{condition code} contents can be reused also.

\footnote{We assume that there are no \textit{aliases} for variables.}
Register Targeting

On some machines, it is useful to be able to tell `genarith`, top-down, that its result should be produced in a certain register if possible.

**Example:** Suppose that a function argument should be transmitted in register `%xmm0`. If the argument can be generated in `%xmm0` directly, it will save a move instruction.
x86 Processor

We will assume an x86-64 processor. This processor has a vast number of instructions (some undocumented) and two major families of assembler syntax and calling sequence conventions. We will use the AT&T/Unix syntax and gcc calling conventions.

Integer registers can be used in several sizes, e.g. %eax (32 bits) and %rax (64 bits) are the same register in different sizes. We will assume that integer will use the 32-bit size, while memory addresses must use the 64-bit size.

**General-purpose (Integer) Registers:**
32/64 bits, numbered 0 – 15 in genasm. We will use them in the order %eax, %ecx, %edx, %ebx since %ebx is callee-saved. RBASE to RMAX is the local integer register range.

**Floating Point Registers:**
64 bits, numbered 16 – 31 in genasm. FBASE to FMAX is the floating register range. These are called %xmm0 through %xmm7.
Move (Load/Store) Instructions

Most of the instructions used in a computer program are instructions that move data. The x86 processor uses variable-length instructions and offers very flexible addressing options.

The Unix syntax of x86 instructions shows data movement from left to right:

```
# code for i := 0
movl $0,%eax    # 0 -> %eax
movl %eax,-32(%rbp) # %eax -> i
```

There are three data formats that we will use:

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Terminology</th>
<th>Bits</th>
<th>Use For</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOVL</td>
<td>long</td>
<td>32</td>
<td>Integer</td>
</tr>
<tr>
<td>MOVQ</td>
<td>quad-word</td>
<td>64</td>
<td>Pointer</td>
</tr>
<tr>
<td>MOVSD</td>
<td>signed double</td>
<td>64</td>
<td>Float</td>
</tr>
</tbody>
</table>
Kinds of Move Addressing

There are several addressing styles that are used with move instructions:

**Constants** or *immediate* values are specified with a $. x86 allows even very large integer constants.

```
movl $0,%eax # 0 -> %eax
```

**Stack Variables** have negative offsets relative to %rbp. The offset is the offset from the symbol table minus the stack frame size.

```
movl %eax,-32(%rbp) # %eax -> i
```

In this case, i has an offset of 16 and the stack frame size is 48, so net offset is (16 - 48) = -32.

**Literals** have offsets relative to %rip (current address).

```
movsd .LC5(%rip),%xmm0 # 0.0625 -> %xmm0
```

**Record References** have offsets relative to a register containing a pointer to the record.

```
movl %eax,32(%rcx) # ^ . []
```
Move with Calculated Address

x86 allows very flexible addressing:

**Offset from Register**

\[
\text{movl} \ %\text{eax},-32(\%\text{rbp}) \ # \ %\text{eax} \rightarrow \text{i}
\]

**Offset from Two Registers**

\[
\text{movsd} \ %\text{xmm0},-1296(\%\text{rbp},\%\text{rax}) \ # \ ac[]
\]

The offset and contents of the two registers are added to form the effective address.

**Offset from Two Registers with Multiplier**

\[
\text{movsd} \ %\text{xmm0},-1296(\%\text{rbp},\%\text{rax},8) \ # \ x[]
\]

In this case, the second register is multiplied by 2, 4, or 8 (using an internal shift) before being added. This can allow many aref expressions to be done in a single instruction.
Literals

A *literal* is constant data that is assembled as part of the compiled program. Literals must be made for large integers, all floats, and most strings.

There are three programs that make literals; each is called with a literal value and a label number:

- first do `label = labelnumber++;`
- `makeilit(i,label)`: integer (not needed for x86)
- `makeflit(f,label)`: float
- `makeblit(s,label)`: byte (string)

A literal is accessed relative to the Instruction Pointer:

```
    movsd .LC4(%rip),%xmm1
```

Literals are saved in tables and output at the end of the program.

```
    .align 8
    .LC4:
    .long 0  # little-endian on X86
    .long 1078001664
```
**Integer Arithmetic Instructions**

These instructions operate on registers or memory. $S,D$ represent source and destination. Usually, $S$ is the rhs and $D$ is the lhs.

- **addl** $S,D$ \( D + S \rightarrow D \)
- **subl** $S,D$ \( D - S \rightarrow D \)
- **imull** $S,D$ \( D \times S \rightarrow D \)
- **ldiv** $S,D$ \( D/S \rightarrow D \)
- **cmpl** $S,D$ *compare $D - S$, set condition*
- **andl** $S,D$ \( D \land S \rightarrow D \)
- **orl** $S,D$ \( D \lor S \rightarrow D \)
- **notl** $D$ \( \neg D \rightarrow D \)
- **negl** $D$ \( -D \rightarrow D \)

Note that arithmetic can be done directly on memory: $i := i + 1$ can be one instruction:

\[
\text{addl } \$1,-32(%rbp)
\]

---

39for **ldiv**, $D$ must be $\%eax$, and **cdq** must be used before the divide to sign-extend $\%eax$ into $\%edx$, which of course changes $\%edx$. 

233
Compare and Jump

A *compare* is a subtract that does not store its results; however, the results set the *condition code* register, which can then be tested by jump instructions.

\[
\begin{align*}
\text{cmpl} & \quad S,D \quad \text{compare } D - S, \text{ set condition, integer} \\
\text{cmpq} & \quad S,D \quad \text{compare } D - S, \text{ set condition, pointer} \\
\text{comisd} & \quad S,D \quad \text{compare } D - S, \text{ set condition, float}
\end{align*}
\]

- **C** Carry
- **O** Overflow

Condition code bits: 
- \( < < 0 \)
- \( = = 0 \)
- \( > > 0 \)

The jump instructions test the condition code:

\[
\begin{align*}
\text{jmp} & \quad \text{Jump always.} \\
\text{jle} & \quad \text{Jump if } D \leq S \\
\text{je} & \quad \text{Jump if } D = S \\
\text{jne} & \quad \text{Jump if } D \neq S \\
\text{jge} & \quad \text{Jump if } D \geq S \\
\text{jl} & \quad \text{Jump if } D < S \\
\text{jg} & \quad \text{Jump if } D > S
\end{align*}
\]
Floating Point

These instructions operate on registers or memory. \( S,D \) represent source and destination.

- **addsd** \( S,D \) \( D + S \rightarrow D \)
- **subsd** \( S,D \) \( D - S \rightarrow D \)
- **mulsd** \( S,D \) \( D \times S \rightarrow D \)
- **divsd** \( S,D \) \( D/S \rightarrow D \)
- **cmpsd** \( S,D \) *compare* \( D - S\), *set condition*

Routines are provided to generate the instruction sequences for **fix**, **float** and **negate** operations.
Intrinsic Functions

Some things that are specified as functions in source code should be compiled in-line. These include:

1. Type-change functions that act as the identity function: \texttt{boole}, \texttt{ord}, \texttt{chr}.
2. Functions that are only a few instructions: \texttt{pred (- 1)}, \texttt{succ (+ 1)}, \texttt{abs}.
3. Functions that are implemented in hardware: \texttt{sqrt} may be an instruction.
Function Calls

For external functions, it is necessary to:

1. Set up the arguments for the function call.
2. Call the function.
3. Retrieve the result and do any necessary final actions.

A function call involves the following:

1. Load arguments into registers:
   - First integer argument in `%edi`
   - For string literal, address in `%rdi` using `leaq`
     (Load Effective Address, Quad):
     ```
     leaq .LC4(%rip),%rdi  # addr literal .LC4
     ```
   - First floating argument in `%xmm0`

2. Execute a `call` instruction\(^{40}\):
   ```
   call sin@PLT
   ```

3. Floating results are returned in `%xmm0`. Integer results are returned in `%eax` or `%rax`.

\(^{40}\)PLT is the Procedure Linkage Table for dynamically linked procedures.
Volatile Registers

By convention, some registers may be designated:

- **volatile** or **caller-saved**: assumed to be destroyed by a subroutine call.

- **non-volatile** or **callee-saved**: preserved (or not used) by a subroutine.

We will use the registers %eax, %ecx, %edx, and %ebx; %ebx is callee-saved, but is saved in the preamble and restored in the postamble.

Any floating values that need to be preserved across a call must be saved on the stack prior to the call and restored afterwards. Routines are provided to save one floating register on the stack and restore it.
Details of Function Call

1. For each argument, use \texttt{genarith} to compute the argument. If needed, move the result from the register returned by \texttt{genarith} to \%xmm0 and mark the \texttt{genarith} register unused.

2. Return the function result register (\%xmm0, \%eax or \%rax) as the result of \texttt{genarith}.

If the rhs of an operation involves a function call, as in

\[
y := \exp(-x)*\sin(c*x)
\]

1. If the lhs register is in use, save it on the stack.
2. Call the function
3. Get a new register, restore the lhs value to it from the stack, and set the lhs register to that register.
IF Statement Generation

Code for an intermediate code statement of the form (if c p1 p2) can be generated as follows:

1. Generate code for the condition c using the arithmetic expression code generator. Note that a cmp instruction should be generated for all comparison operators, regardless of which comparison is used.

2. Generate the appropriate jump-on-condition instruction, denoted jmp c below, by table lookup depending on the comparison operator.

```
genarith(c)  # always generates cmp
jmp c       .L1  # jump if c true = then
gend(p2)    # "else"
jmp    .L2  # jump to end
.L1:
gen(p1)    # "then"
.L2:        # end
```

The following jump table can be used:

<table>
<thead>
<tr>
<th>op</th>
<th>=</th>
<th>≠</th>
<th>&lt;</th>
<th>≤</th>
<th>≥</th>
<th>&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>je</td>
<td>jne</td>
<td>jl</td>
<td>jle</td>
<td>jge</td>
<td>jg</td>
</tr>
<tr>
<td>-c</td>
<td>jne</td>
<td>je</td>
<td>jge</td>
<td>jg</td>
<td>jl</td>
<td>jle</td>
</tr>
</tbody>
</table>
IF Statement Optimization

Special cases of IF statements are common; these can be compiled as shown below, where \texttt{jmp c} represents a jump on condition and \texttt{jmp -c} represents a jump on the opposite of a condition.

\[
\begin{align*}
&\text{(if}\ c\ \text{(goto}\ l))\quad \text{jmp}\ c\ l \\
&(\text{if}\ c\ \text{(progn)}\ \text{(goto}\ l))\quad \text{jmp}\ -c\ l \\
&(\text{if}\ c\ p1\ \text{(goto}\ l))\quad \text{jmp}\ -c\ l \quad p1 \\
&(\text{if}\ c\ \text{(goto}\ l)\ p2)\quad \text{jmp}\ c\ l \quad p2 \\
&(\text{if}\ c\ p1)\quad \text{jmp}\ -c\ L1 \quad p1 \\
&\text{L1:} \\
&(\text{if}\ c\ \text{(progn)}\ p2)\quad \text{jmp}\ c\ L1 \quad p2 \\
&\text{L1:}
\end{align*}
\]
Array References

Suppose the following declarations have been made:

```plaintext
var i: integer; x: array[1..100] of real;
```

Assume that \( i \) has an offset of 4 and \( x \) has an offset of 8 (since \( x \) is `double`, its offset must be 8-aligned.). The total storage is 808. A reference \( x[i] \) would generate the code:

```plaintext
(AREF X (+ -8 (* 8 I))
```

The effective address is: `%rbp`, minus stack frame size, plus the offset of \( x \), plus the expression \( (+ -8 (* 8 I)) \).
Easy Array References

((AREF X (+ -8 (* 8 I))))

One way to generate code for the array reference is to:

- use `genarith` to generate `(+ -8 (* 8 I))` in register `%eax` (move the result to `%eax` if necessary).
- Issue the instruction `CLTQ` (Convert Long To Quad), which sign-extends `%eax` to `%rax`.
- Access memory from the offset and sum of the registers.

```
movsd %xmm0,-1296(%rbp,%rax) # ac[]
```

This is easy from the viewpoint of the compiler writer, but it generates many instructions, including a possibly expensive multiply.
Better Array References

\[(\text{AREF } X (+ -8 (* 8 I)))\]

A better way generate the array reference is to:

1. combine as many constants as possible (constant folding)
2. replace the multiply with a shift

Note that in the expression \((+ -8 (* 8 I))\) there is an additive constant of \(-8\) and that the multiply by 8 can be done in the x86 processor by a shift of 3 bits, which can be done for free by the instruction.

This form of code can be generated as one instruction on x86, assuming that \(i\) is in \%rax:

\[
\text{movsd } \%xmm0,-208(\%rbp,\%rax,8)
\]
Pointer References

A pointer operator specifies indirect addressing. For example, in the test program, the code `john^ . favorite` produces the intermediate code:

\[(\text{aref} (\sim \text{john}) \ 32)\]

Note that a pointer operator can occur in Pascal only as the first operand of an `aref`, and in this case the offset is usually a constant. Compiling code for it is simple: the address is the sum of the pointer value and the offset:

\[
\text{movq} \ -1016(\%rbp),\%rcx \ # \ \text{john} \rightarrow \%rcx \\
\text{movl} \ %eax,32(\%rcx) \ # \ ^. \ [\]
\]

This example shows a store of `%eax` into memory at a location 32 bytes past the pointer value in the variable `john`. 
switch Statement

The `switch` statement is usually evil:

- generates lots of code (lots of `if` statements)
- takes time to execute
- poor software engineering.

```c
int vowel(ch)
    int ch;
    { int sw;
        switch ( ch )
        { case 'A': case 'E': case 'I':
            case 'O': case 'U': case 'Y':
                sw = 1; break;
            default: sw = 0; break;
        }
        return (sw);
    }
```
switch Statement Compiled

vowel:
    save %sp,-104,%sp
    st %i0,[%fp+68]
.L14:
    ba .L16
    nop
.L17:
    .L18:
    .L19:
    .L20:
    .L21:
    .L22:
        mov 1,%o0
        ba .L15
        st %o0,[%fp-8]
.L23:
    !    default: sw = 0; break;
        ba .L15
        st %g0,[%fp-8]
.L16:
    ld [%fp+68],%o0
    cmp %o0,79
    bge .L_y0
    nop
    cmp %o0,69
    bge .L_y1
    nop
    cmp %o0,65
    be .L17
    nop
    ba .L23
    nop
.L_y1:
    be .L18
    nop
    ... 20 more instructions
.L24:
    .L15:
        ld [%fp-8],%i0
        jmp %i7+8
restore
switch Statement Compiled -0

[ ... big table constructed by the compiler ... ]
vowel:

```
sub  %o0,65,%g1
cmp  %g1,24
bg   .L77000008
sethi %hi(.L_const_seg_900000102),%g2
.L9000000107:
sll  %g1,2,%g1
add  %g2,%lo(.L_const_seg_900000102),%g2
ld   [%g1+%g2],%g1
jmpl %g1+%g2,%g0
nop
.L770000007:
or  %g0,1,%g1
retl ! Result = %o0
or   %g0,%g1,%o0
.L770000008:
or  %g0,0,%g1
retl ! Result = %o0
or   %g0,%g1,%o0
```
Table Lookup

static int vowels[]
    = {1,0,0,0,1,0,0,0,1,0,0,0,0,
       0,1,0,0,0,0,0,1,0,0,0,1,0};

int vowel(ch)
    int ch;
    {
        int sw;
        sw = vowels[ch - 'A'];
        return (sw);
    }


Table Lookup Compiled

vowel:
  save  %sp,-104,%sp     
st   %i0,[%fp+68]      

.L15:
  ld   [%fp+68],%o0    
sll  %o0,2,%o1       
sethi  %hi(vowels-260),%o0    
or  %o0,%lo(vowels-260),%o0  
  ld   [%o1+%o0],%i0    
st   %i0,[%fp-8]      
jmp  %i7+8            
restore
Table Lookup Compiled -0

vowel:

sll %o0,2,%g1
sethi %hi(vowels-260),%g2
add %g2,%lo(vowels-260),%g2
retl ! Result = %o0
ld [%g1+%g2],%o0 ! volatile

Bottom Line:

switch 46
switch -0 15
Table Lookup 10
Table Lookup -0 5

Table Lookup beats the switch statement in code size and performance; it is also better Software Engineering.
There are several methods of passing parameters between calling program and subroutine:

1. **Call by Reference:** The *address* of the parameter is passed. The storage of the actual parameter is used (and possibly modified). Used by Fortran, Pascal for *var* parameters, C for arrays.

2. **Call by Pointer:** A pointer to the parameter is passed by value. Used in Lisp, in Java for reference types (any capital-letter type). In some cases, parts of the object that is pointed to can be changed.

3. **Call by Value:** The *value* of the parameter is copied into the subroutine. Modifications are not seen by the caller. Expensive for large data, e.g. arrays. Used in Pascal, Java, C for basic types.

4. **Call by Value - Result:** The value of the parameter is copied into the subroutine, and the result is copied back upon exit. (Ada)

5. **Call by Name:** The effect is that of a *textual substitution* or macro-expansion of the subroutine into the caller’s environment. Trouble-prone, hard to implement, slow. Used in Algol.
Reference vs. Value

*Actual parameter:* the value of the parameter in the calling program. *Formal parameter:* the name of the parameter in the subroutine.

A call creates a *binding* between the formal parameter name in the subroutine and the actual parameter value in the call.

Call by reference and call by value have opposite advantages and disadvantages:

<table>
<thead>
<tr>
<th>Call by:</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>Fast for Arrays</td>
<td>Possibly Dangerous</td>
</tr>
<tr>
<td>Value</td>
<td>Safe</td>
<td>Slow for Arrays</td>
</tr>
</tbody>
</table>

Usually, we want to use call by value for small values such as numbers and call by reference for arrays.

**Main:**

```
i = 3;
foo(j):  j = j + 1;
foo(i);
print j;
print i;
```

**Results:**

*Value:*  
\[ j = 4, i = 3 \]

*Reference:*  
\[ j = 4, i = 4 \]
Aliasing

An *alias* is the creation of a second name for the same storage. This can create unexpected results and should generally be avoided.

Main:

```plaintext
i = 24;
foo(i, i);
print i;
```

foo(j, k):

```plaintext
j = k / 4;
k = k + 5;
print j, k;
```

Results: Value: j = 6, k = 29, i = 24

Reference: j = 11, k = 11, i = 11

Using call by reference, we have created three aliases i, j, and k that all refer to the same storage location.

Aliasing causes problems for compiler optimization by creating unexpected side-effects.
Macros

A *macro* is a function from code to code, usually turning a short piece of code into a longer code sequence.

Lisp macros produce Lisp code as output; this code is executed or compiled.

```lisp
(defun neq (x y) (not (eq x y)))
```

```lisp
(defun neq (x y) (list 'not (list 'eq x y)))
```

```lisp
(defun neq (x y) '(not (eq ,x ,y)))
```

In C, *#define* *name* *pattern* specifies a textual substitution. If *pattern* contains an operation, it should be parenthesized.

```c
#define sum x + y    /* needs parens */
```

```c
z = sum * sum;
```
In-line Compilation

*In-line* or *open* compilation refers to compile-time expansion of a subprogram, with substitution of arguments, in-line at the point of each call.

**Advantages:**

- Eliminates overhead of procedure call
- Can eliminate method lookup in an object-oriented system
- Can expose opportunities for optimization across the procedure call, especially with OOP: more specific types become exposed.
- Relative saving is high for small procedures

**Disadvantages:**

- May increase code size
Optimization

Program optimization can be defined as follows:

Given a program P, produce a program P’ that produces the same output values as P for any given input, but has a lower cost.

Typical costs are execution time and program space. Most optimizations target time; fortunately, the two usually go together.

Optimization is an economic activity:

- **Cost:** a larger and sometimes slower compiler.
- **Benefit:**
  - Amount saved by the code improvement
    * number of occurrences in code
    * number of repetitions in execution
    * number of uses of the compiled code

It is not possible to optimize everything. The goal is to find leverage: cases where there is a large expected payoff for a small cost.
Correctness of Optimization

Optimization must never introduce compiler-generated errors! A program that runs faster but produces incorrect results is not an improvement.

There are often cases where an optimization will nearly always be correct.

\[
\text{if ( } x \ast n == y \ast n \text{ ) \ldots}
\]

might be optimized to:

\[
\text{if ( } x == y \text{ ) \ldots}
\]

Is this correct?

In general, one must be able to prove that an optimized program will always produce the same result.
Optional Optimization

Some compilers either allow the optimizer to be turned off, or require that optimization be requested explicitly.

Reasons for turning optimization off:

- Compilation may be faster.
- If the optimizer produces errors, the errors can be avoided.

With some sophisticated compilers, the users normally turn the optimizer off! This is because the optimizer has the reputation of generating incorrect code.

Optimizations that don’t take much compilation time and are guaranteed to be correct should probably be done every time. A slightly longer compilation time is almost always compensated by faster execution.
Local and Global Optimization

Local optimization is that which can be done correctly based on analysis of a small part of the program. Examples:

- Constant folding: $2 \times 3.14 \rightarrow 6.28$
- Reduction in strength: $x \times 2 \rightarrow x + x$
- Removing branches to branches:

  \[
  L1: \quad \text{Goto} \quad L2
  \]

Global optimization requires information about the whole program to be done correctly. Example:

\[
\begin{align*}
I \times 8 & \quad \Rightarrow \quad R1 = I \times 8 \\
\ldots & \\
I \times 8 & \quad \Rightarrow \quad R1
\end{align*}
\]

This is correct only if $I$ is not redefined between the two points. Doing optimization correctly requires program analysis: a special-purpose proof that program $P'$ produces the same output values as $P$. 
Easy Optimization Techniques

Some good optimization techniques include:

1. Generation of good code for common special cases, such as \( i = 0 \). These occur frequently enough to provide a good savings, and testing for them is easy.

2. Generation of good code for subscript expressions.
   - Code can be substantially shortened.
   - Subscript expressions occur often in code.
   - Subscript expressions occur inside loops.

3. Assigning variables to registers.
   - Much of code is loads and stores. A variable that is in a register does not have to be loaded or stored.
   - Easy case: assign a loop index variable to a register inside the loop.
   - General case: graph coloring for register assignment.

4. Reduction in strength: \( x \ast 8 \rightarrow x \ll 3 \)
Constant Folding

*Constant folding* is performing operations on constants at compile time:

\[
x = \text{angle} \times 3.1415926 / 180.0
\]

\[
y = \text{sqrt}(2.0)
\]

\[
z = \text{a}[3]
\]

The savings from doing this on programmer expressions is minor. However, there can be major savings by optimizing:

1. Subscript expressions generated by the compiler.

Constant folding should not allow the programmer to “break” the compiler by writing a bad expression: \texttt{sqrt(-1.0)}. 
Peephole Optimization

Certain kinds of redundancies in generated code can be corrected by making a linear pass over the output code and transforming patterns seen within a small local area (called the *peephole*):

```
STA X
LDA X
```

```
JMP L17
```

```
L17:
```

However,

*It is more blessed to generate good code in the first place than to generate bad code and then try to fix it.*
Loop Unrolling

*Loop unrolling* is the compile-time expansion of a loop into repetitions of the code, with the loop index replaced by its value in each instance.

```c
for (i = 0; i < 3; i++)
    disp[i] = c2[i] - c1[i];
```

is expanded into:

```c
disp[0] = c2[0] - c1[0];
```

<table>
<thead>
<tr>
<th>Loop:</th>
<th>Executed:</th>
<th>Instructions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unrolled:</td>
<td>57</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
</tr>
</tbody>
</table>

The second form runs faster, and it may generate less code. This is a useful optimization when the size of the loop is known to be a small constant at compile time.

*Modulo unrolling* unrolls a loop modulo some chosen constant. This can significantly reduce the loop overhead without expanding code size too much.
Partial Evaluation

Partial evaluation is the technique of evaluating those parts of a program that can be evaluated at compile time, rather than waiting for execution time.

For example, the rotation of a point in homogeneous coordinates by an angle $\theta$ around the $x$ axis is accomplished by multiplying by the matrix:

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos \theta & -\sin \theta & 0 \\
0 & \sin \theta & \cos \theta & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Many of the cycles consumed in the matrix multiply would be wasted because they would be trivial computations (e.g., multiplying by 1 or adding 0).

By unrolling the loops of matrix multiply, substituting the values from the coefficient matrix, and performing partial evaluation on the result, a specialized version of the matrix multiply can be obtained. This version saves many operations:

<table>
<thead>
<tr>
<th>Version:</th>
<th>Load</th>
<th>Store</th>
<th>Add/Sub</th>
<th>Mul</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>128</td>
<td>16</td>
<td>48</td>
<td>64</td>
<td>256</td>
</tr>
<tr>
<td>Specialized</td>
<td>24</td>
<td>16</td>
<td>8</td>
<td>16</td>
<td>64</td>
</tr>
</tbody>
</table>
Partial Evaluation

Partial evaluation specializes a function with respect to arguments that have known values. Given a program $P(x, y)$ where the values of variables $x$ are constant, a specializing function $\text{mix}$ transforms $P(x, y) \rightarrow P_x(y)$ such that $P(x, y) = P_x(y)$ for all inputs $y$. $P_x(y)$ may be shorter and faster than $P(x, y)$. We call $x$ static data and $y$ dynamic data.

Partial evaluation involves:

- precomputing constant expressions involving $x$,
- propagating constant values,
- unfolding or specializing recursive calls,
- reducing symbolic expressions such as $x \times 1$, $x \times 0$, $x + 0$, $(\text{if true } S_1 S_2)$.

A good rule of thumb is that an interpreted program takes ten times as long to execute as the equivalent compiled program. Partial evaluation removes interpretation by increasing the binding between a program and its execution environment.

---

Example

Suppose we have the following definition of a function \texttt{power(x,n)} that computes \(x^n\):

\[
(\text{defun power (x n)}
\quad \text{(if (= n 0)}
\quad \quad 1
\quad \quad \text{(if (evenp n)}
\quad \quad \quad (\text{square (power x (/ n 2)})
\quad \quad \quad (* x (power x (- n 1)))))
\quad \text{))}
\]

If this is used with a constant argument \(n\), as is often the case, the function can be partially evaluated into more efficient code:

\[
(\text{gldefun t3 ((x real)) (power x 5))}
\]

\[
(\text{glcp 't3})
\]
\text{result type: REAL}
\[
(\text{LAMBDA (X) (* X (SQUARE (SQUARE X))))}
\]

The recursive function calls and interpretation (\texttt{if} statements) have been completely removed; only computation remains. Note that the constant argument 5 is gone and has been converted into control.
Simple Partial Evaluator

(defun mix (code env)
  (let (args test fn)
    (if (constantp code) ; a constant
        code ; evaluates to itself
      (if (symbolp code) ; a variable
          (if (assoc code env) ; bound to a constant
              (cdr (assoc code env)) ; evals to that constant
              code) ; else to itself
      (if (consp code)
          (progn
            (setq fn (car code))
            (if (eq fn 'if) ; if is handled
                (progn ; specially
                  (setq test (mix (cadr code) env))
                  (if (eq test t) ; if true
                      (mix (caddr code) env) ; then part
                    (if (eq test nil) ; if false
                        (mix (cadddr code) env) ; els
                      (cons 'if
                        (cons test
                          (mapcar #'(lambda (x)
                                      (mix x env))
                                (cddr code))))))))))
Simple Partial Evaluator...

(progn ; (fn args)
  (setq args (mapcar #'(lambda (x)
            (mix x env)) ; mix the args
            (cdr code))
  (if (and (every #'constantp args) ; if all constant
            (not (member fn '(print ; and no
            prin1 princ error ; compile-time
            format))))) ; side-effects
            (kwote (eval (cons fn args))) ; eval it now
  (if (and (some #'constantp args); if some constant
            (fndef fn)) ; & symbolic fn
            (fnmix fn args) ; unfold the fn
            (fnopt (cons fn args)))))) ; optimize result

(cons 'bad-code code) ) ) ) )

269
Examples

>(load "/u/novak/cs394p/mix.lsp")
>(mix 'x '((x . 4)))
4
>(mix '(if (> x 2) 'more 'less) '((x . 4)))
'MORE

(defun power (x n)
  (if (= n 0)
      1
      (if (evenp n)
          (square (power x (/ n 2)))
          (* x (power x (- n 1)))))

>(fnmix 'power '(x 3))
(* X (SQUARE X))

>(specialize 'power '(x 3) 'cube)
>(fndef 'cube)
(LAMBDA (X) (* X (SQUARE X)))
> (cube 4)
64

>(fnmix 'power '(x 22))
(SQUARE (* X (SQUARE (* X (SQUARE (SQUARE X)))))))
Examples

; append two lists
(defun append1 (l m)
  (if (null l)
      m
      (cons (car l) (append1 (cdr l) m))))

>(fnmix 'append1 '(1 2 3) m)
(CONS 1 (CONS 2 (CONS 3 m)))
Binding-Time Analysis

*Binding-time analysis* determines whether each variable is static (S) or dynamic (D).

- Static inputs are S and dynamic inputs are D.
- Local variables are initialized to S.
- Dynamic is contagious: if there is a statement
  \[ v = f(...D...) \]
  then \( v \) becomes D.
- Repeat until no more changes occur.

Binding-time analysis can be *online* (done while specialization proceeds) or *offline* (done as a separate preprocessing phase). Offline processing can *annotate* the code by changing function names to reflect whether they are static or dynamic, e.g. \texttt{if} becomes \texttt{ifs} or \texttt{ifd}.
**Futamura Projections**

Partial evaluation is a powerful unifying technique that describes many operations in computer science.

We use the notation $[P]_L$ to denote running a program $P$ in language $L$. Suppose that $\text{int}$ is an interpreter for a language $S$ and $\text{source}$ is a program written in $S$. Then:

\[
\text{output} = [\text{source}]_S[\text{input}] \\
= [\text{int}][\text{source}, \text{input}] \\
= [[[\text{mix}][\text{int}, \text{source}] innov][\text{input}] \\
= [\text{target}][\text{input}]
\]

Therefore, $\text{target} = [[\text{mix}][\text{int}, \text{source}]$.

\[
\text{target} = [[\text{mix}][\text{int}, \text{source}] \\
= [[[\text{mix}][\text{mix}, \text{int}]][\text{source}] \\
= [\text{compiler}][\text{source}]
\]

Thus, $\text{compiler} = [[\text{mix}][\text{mix}, \text{int}] = [\text{cogen}][\text{int}]$

- Finally, $\text{cogen} = [[\text{mix}][\text{mix}, \text{mix}] = [\text{cogen}][\text{mix}]$

is a *compiler generator*, i.e., a program that transforms interpreters into compilers.

---

Interpreter

This program is an interpreter for arithmetic expressions using a simulated stack machine.

```
(defun topinterp (exp) ; interpret, pop result
  (progn (interp exp)
          (pop *stack*))

(defun interp (exp)
  (if (consp exp) ; if op
      (if (eq (car exp) '+)
          (progn (interp (cadr exp)) ; lhs
                  (interp (caddr exp)) ; rhs
                  (plus)) ; add
          (if ...)) ; other ops
      (pushopnd exp))) ; operand

(defun pushopnd (arg) (push arg *stack*))

(defun plus ()
  (let ((rhs (pop *stack*))
        (pushopnd (+ (pop *stack*) rhs))))

>(topinterp '(+ (* 3 4) 5))
17
```
Specialization

The interpreter can be specialized for a given input expression, which has the effect of compiling that expression.

\[(\text{topinterp '}(+ (* 3 4) 5))\]
17

\[(\text{specialize 'topinterp '('}(+ (* a b) c))
'expr1 ')(a b c))\]

\[(\text{pp expr1})\]

\((\text{LAMBDA-BLOCK EXPR1 (A B C)})
(\text{PROGN}
 (\text{PUSH A *STACK*})
 (\text{PUSH B *STACK*})
 (\text{TIMES})
 (\text{PUSH C *STACK*})
 (\text{PLUS})
 (\text{POP *STACK*}))\)

\[(\text{expr1 3 4 5})\]
17
Parameterized Programs

A highly parameterized program is easier to write and maintain than many specialized versions for different applications, but may be inefficient.

**Example:** Draw a line: \((x_1, y_1)\) to \((x_2, y_2)\).

Options include:

- Width of line (usually 1)
- Color
- Style (solid, dashed, etc.)
- Ends (square, beveled)

If all of these options are expressed as parameters, it makes code longer, makes calling sequences longer, and requires interpretation at runtime. Partial evaluation can produce efficient specialized versions automatically.
Pitfalls of Partial Evaluation

There are practical difficulties with partial evaluation:

- To be successfully partially evaluated, a program must be written in the right way. There should be good *binding time separation*: avoid mixing static and dynamic data (which makes the result dynamic).

\[
\text{(lambda (x y z) (lambda (x y z) (+ (+ x y) z)) (+ x (+ y z)))}
\]

- The user may have to give advice on when to unfold recursive calls. Otherwise, it is possible to generate large or infinite programs.

One way to avoid this is to require that recursively unfolding a function call must make a constant argument smaller according to a well-founded ordering. Branches of dynamic *if* statements should not be unfolded.
Pitfalls ...

- Repeating arguments can cause exponential computation duplication: 43

\[
\begin{align*}
\text{(defun } f \ (n) & \\
& (\text{if } (= \ n \ 0) \\
& \quad 1 \\
& \quad (g \ (f \ (- \ n \ 1))) \ ) \ ) \\
\text{(defun } g \ (m) \ (+ \ m \ m))
\end{align*}
\]

- The user should not have to understand the logic of the output program, nor understand how the partial evaluator works.

- Speedup of partial evaluation should be predictable.

- Partial evaluation should deal with typed languages and with symbolic facts, not just constants.

\[\text{43 Jones et al., p. 119.}\]
Program Analysis

To correctly perform optimizations such as moving invariant code out of loops or reusing common subexpressions, it is necessary to have global information about the program.\textsuperscript{44}

*Control flow analysis* provides information about the potential control flow:

- Can control pass from one point in the program to another?
- From where can control pass to a given point?
- Where are the loops in the program?

*Data flow analysis* provides information about the definition and use of variables and expressions. It can also detect certain types of programmer errors.

- Where is the value of a variable assigned?
- Where is a given assignment used?
- Does an expression have the same value at a later point that it had at an earlier point?

Basic Block

A *basic block* (or *block* for short) is a sequence of instructions such that if any of them is executed, all of them are. That is, there are no branches in except at the beginning and no branches out except at the end.

begin
  \[ i := j; \]
  \[ \text{if } i > k \]
  \[ \quad \text{then begin } k := k + 1; i := i - 1 \text{ end} \]
  \[ \text{else } i := i + 1; \]
  \[ \text{writeln}(i) \]
end
Finding Basic Blocks

Basic blocks are easily found by a compiler while processing a program.

A *leader* is the first statement of a basic block:

1. the first statement of a program
2. any statement that has a label or is the target of a branch
3. any statement following a branch

A basic block is a leader and successive statements up to the next leader.

Note that branch statements themselves do not appear in basic blocks, although the computation of the condition part of a conditional branch will be included.

In a graph representation of a program, basic blocks are the nodes of the graph, and branches are the arcs between nodes.
Relations and Graphs

The *cartesian product* of two sets $A$ and $B$, denoted $A \times B$, is the set of all ordered pairs $(a, b)$ where $a \in A$ and $b \in B$.

A *relation* between two sets is a subset of their cartesian product.

A *graph* is a pair $(S, \Gamma)$ where $S$ is a set of nodes and $\Gamma \subseteq S \times S$.

Properties of relations:

<table>
<thead>
<tr>
<th>Property</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflexive</td>
<td>$\forall a \quad (a, a) \in R$</td>
</tr>
<tr>
<td>Symmetric</td>
<td>$\forall a, b \quad (a, b) \in R \rightarrow (b, a) \in R$</td>
</tr>
<tr>
<td>Transitive</td>
<td>$\forall a, b, c \quad (a, b) \in R \land (b, c) \in R \rightarrow (a, c) \in R$</td>
</tr>
<tr>
<td>Antisymmetric</td>
<td>$\forall a, b \quad (a, b) \in R \land (b, a) \in R \rightarrow a = b$</td>
</tr>
</tbody>
</table>

A relation that is reflexive, symmetric, and transitive is an *equivalence relation*, which corresponds to a *partition* of the set (a set of disjoint subsets whose union is the set).

A relation that is reflexive, antisymmetric, and transitive is a *partial order*. Example: $\leq$. 
Graph Notations

Let \((S, \Gamma)\) be a graph and \(b \in S\) be a node.

\[\Gamma b = \{x \in S \mid (b, x) \in \Gamma\}\]

are the nodes that are *immediate successors* of \(b\).

\[\Gamma^+ b = \{x \in S \mid (b, x) \in \Gamma^+\}\]

are the nodes that are *successors* of \(b\).

\[\Gamma^{-1} b = \{x \in S \mid (x, b) \in \Gamma\}\]

are the nodes that are *immediate predecessors* of \(b\).

Let \(A \subset S\) be a subset of the set of nodes \(S\).

\[\Gamma A = \{y \in S \mid (x, y) \in \Gamma \land x \in A\}\]

is the set of nodes that are *immediate successors* of nodes in \(A\).

\[\Gamma^{-1} A = \{x \in S \mid (x, y) \in \Gamma \land y \in A\}\]

is the set of nodes that are *immediate predecessors* of nodes in \(A\).

We say \((A, \Gamma_A)\) is a *subgraph* of \((S, \Gamma)\), where

\[\Gamma_A x = \Gamma x \cap A\]

is the set of transitions within the subgraph.
Bit Vector Representations

Subsets of a finite set can be efficiently represented as bit vectors, in which a given bit position is a 1 if the corresponding item is an element of the subset. Representing a 128-element set takes only 4 32-bit words of memory.

Operations on sets can be done on whole words.

<table>
<thead>
<tr>
<th>Set operation:</th>
<th>Bit vector operation:</th>
</tr>
</thead>
<tbody>
<tr>
<td>∈</td>
<td>∧ with vector for element or test bit</td>
</tr>
<tr>
<td></td>
<td>∧</td>
</tr>
<tr>
<td>∪</td>
<td>∨</td>
</tr>
<tr>
<td>set complement of $A$</td>
<td>$\neg A$</td>
</tr>
<tr>
<td>set difference, $A - B$</td>
<td>$A \land \neg B$</td>
</tr>
</tbody>
</table>

Operations on the bit vector representation are $O(n/32)$, compared to $O(n \cdot m)$ with other methods.

Example: assign a bit for each program variable or subexpression.
Boolean Matrix Representation of Graph

A relation $R$ or graph on a finite set can be expressed as a boolean matrix $M$ where:

$$M[i, j] = 1 \iff (i, j) \in R.$$ 

Multiplication of boolean matrices is done in the same way as ordinary matrix multiplication, but using $\land$ for $\cdot$ and $\lor$ for $+$.

<table>
<thead>
<tr>
<th>Property</th>
<th>Matrix:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identity, $R^0$</td>
<td>$I_n$ (identity matrix)</td>
</tr>
<tr>
<td>Inverse, $R^{-1}$ or $\Gamma^{-1}$</td>
<td>$M^T$</td>
</tr>
<tr>
<td>Reflexive</td>
<td>$I \subseteq M$</td>
</tr>
<tr>
<td>Symmetric</td>
<td>$M = M^T$</td>
</tr>
<tr>
<td>Transitive</td>
<td>$M^2 \subseteq M$</td>
</tr>
<tr>
<td>Antisymmetric</td>
<td>$M \cap M^T \subseteq I_n$</td>
</tr>
<tr>
<td>Paths of length $n$</td>
<td>$M^n$</td>
</tr>
<tr>
<td>Transitive closure $\Gamma^+$</td>
<td>$\cup_{i=1}^{n} M^i$</td>
</tr>
<tr>
<td>Reflexive transitive closure $\Gamma^*$</td>
<td>$\cup_{i=0}^{n} M^i$</td>
</tr>
</tbody>
</table>

Example: Let the set $S$ be basic blocks of a program and $\Gamma$ be transfers of control between blocks.
Dominators

Let $e$ denote the first block of a program. A node $d$ dominates a node $n$ iff every simple path from $e$ to $n$ passes through $d$.

For a given node $n$, its immediate dominator is the dominator closest to it. A tree structure is formed by immediate dominators, with $e$ being the root of the tree.

A loop header $h$ dominates all the nodes in the loop. A back edge is an edge $n \rightarrow h$ where $h$ dominates $n$.

The dominator relation allows the program graph to be ordered in a topological sort, which helps in data flow analysis.
Data Flow Analysis: Definition and Reference of Variables

We assume that each variable is assigned a unique bit number so that it can be used in bit vectors. Likewise, each compiler variable or subexpression $\alpha \leftarrow a \circ b$ is assigned a bit number.

A variable is defined each time it is assigned a value. A variable is referenced (used) whenever its value is read.

The statement $x := a \times b$ first references $a$ and $b$ and then defines $x$.

The statement $x := x + 1$ references $x$ and then defines $x$.

A computation $a \circ b$ is redundant if its value is available in some variable $\alpha$.

A subexpression is computed whenever it appears in an expression. A subexpression is killed if any of its components is defined or killed.

The statement $x[i*3] := a \times b$ computes $a \times b$ and $i \times 3$ and kills $x[anything]$.
Data Flow Analysis for a Block

Computed and killed vectors for a basic block can be found as follows:

• initially, $comp := \emptyset$ and $kill := \emptyset$.

• for each statement $v := a \odot b$ where $\alpha \leftarrow a \odot b$
  1. $comp := comp \cup \{\alpha\}$
  2. $kill := kill \cup kill_v$
  3. $comp := (comp - kill_v) \cup \{v\}$

where $kill_v$ is the set of all expressions involving $v$ directly or indirectly and $(comp - kill_v)$ is set difference.

Example: $I := I + 1$
This statement first computes the expression $I + 1$, but then it kills it because it redefines $I$. 
Availability of Expressions

The expression $\alpha \leftarrow a \circ b$ is available at a point $p$ if the value of the variable $\alpha$ is the same as the value of $a \circ b$ computed at the point $p$.

The expression $\alpha$ is available on entry to block $b$ iff $\alpha$ is available on exit from all immediate predecessors of $b$.

$$avail_{\text{entry}}(b) = \cap_{x \in \Gamma^{-1}b} avail_{\text{exit}}(x)$$

The expression $\alpha$ is available on exit from block $b$ iff $\alpha$ is available at the last point of $b$.

$$avail_{\text{exit}}(b) = (avail_{\text{entry}}(b) - \text{kill}(b)) \cup \text{comp}(b)$$

In general, a system of simultaneous boolean equations may have multiple consistent solutions. It is necessary to compute the maximal solution of the set of boolean equations for intervals at all levels of the derived graph.
Solving Data Flow Equations

If the expressions that are available on entry to a block are known, the values for available on exit can be computed.

For each block $b$ whose predecessors have had their values computed,

$$avail_{entry}(b) = \prod_{x \in \Gamma^{-1}b} avail_{exit}(x)$$

$$avail_{exit}(b) = avail_{entry}(b) \cdot not(kill(b)) + comp(b)$$

No expressions are available on entry to the first block of a program.

The equations can be solved iteratively, using the ordering of the dominator relation, until the values reach a fixpoint. If the inputs to a block change, the values on exit from the block are recomputed, until no more changes occur.
Busy Variables

A dual notion to available is busy.

A variable is busy or live if it will be used before being defined again; otherwise, it is dead.

A variable is busy on entrance to a block $b$ if it is used in block $b$ before being defined, or if it is not defined or killed in block $b$ and is busy on exit from $b$.

A variable is busy on exit from a block $b$ if it is busy on entry to any successor of $b$.

We can define a bit vector referenced, meaning that an expression is referenced in a block before being computed or killed, and solve equations for busy on entrance and busy on exit in a manner analogous to that for the available equations.
Variable Uses and Register Assignment

A def-use chain is the connection between a definition of a variable and the subsequent uses of that variable. When an expression is computed and is busy, the compiler can save its value. When an expression is needed and is available, the compiler can substitute the compiler variable representing its previously computed value.

Register allocation can be performed by graph coloring. A graph is formed in which nodes are def-use chains and (undirected) links are placed between nodes that share parts of the program flow graph.

A graph is colored by assigning “colors” to nodes such that no two nodes that are linked have the same color. Colors correspond to registers.
Register Allocation by Graph Coloring

An undirected graph is colored by assigning a “color” to each node, such that no two nodes that are connected have the same color.

Graph coloring is applied to register assignment in the following way:

- Nodes of this graph correspond to def-use chains.
- Nodes are connected by arcs if the variables are busy at the same time.
- Colors correspond to registers.

A heuristic algorithm is applied to find approximately the minimum number of colors needed to color the graph. If this is more than the number of available registers, spill code is added to reduce the number of colors needed.

By keeping as many variables as possible in registers, the code can be significantly improved.
Overview of Global Optimization

A globally optimizing compiler will perform the following operations:

1. Order nodes using an ordering algorithm to find dominators.
2. Find basic available and busy information for blocks.
3. Solve boolean equations to get available and busy information for each block.
4. Replace common subexpressions by corresponding compiler variables.
5. Assign registers using graph coloring.

The information provided by data flow analysis provides a special-purpose proof that the optimized program is correct (produces the same answers).
gcc Compiler Optimization Options

- **-O** Optimize. Optimizing compilation takes somewhat more time, and a lot more memory for a large function.

  Without `-O`, the compiler’s goal is to reduce the cost of compilation and to make debugging produce the expected results. Statements are independent: if you stop the program with a breakpoint between statements, you can then assign a new value to any variable or change the program counter to any other statement in the function and get exactly the results you would expect from the source code.

  Without `-O`, only variables declared register are allocated in registers.

  With `-O`, the compiler tries to reduce code size and execution time.

- **-fforce-mem** Force memory operands to be copied into registers before doing arithmetic on them. This may produce better code by making all memory references potential common subexpressions. When they are not common subexpressions, instruction combination should eliminate the separate register-load.

- **-fforce-addr** Force memory address constants to be copied into registers before doing arithmetic on them. This may produce better code just as `-fforce-mem` may.

- **-finline** Pay attention the inline keyword. Normally the negation of this option `'-fno-inline'` is used to keep the compiler from expanding any functions inline.

- **-finline-functions** Integrate all simple functions into their callers. The compiler heuristically decides which functions are simple enough to be worth integrating in this way.

- **-fcaller-saves** Enable values to be allocated in registers that will be clobbered by function calls, by emitting extra instructions to save and restore the registers around such calls. Such allocation is done only when it seems to result in better code than would otherwise be produced.

---

45 From the `man gcc` page.
gcc Optimizations

- **-fstrength-reduce** Perform the optimizations of loop strength reduction and elimination of iteration variables.

- **-fthread-jumps** Perform optimizations where we check to see if a jump branches to a location where another comparison subsumed by the first is found. If so, the first branch is redirected to either the destination of the second branch or a point immediately following it, depending on whether the condition is known to be true or false.

- **-funroll-loops** Perform the optimization of loop unrolling. This is only done for loops whose number of iterations can be determined at compile time or run time.

- **-fcse-follow-jumps** In common subexpression elimination, scan through jump instructions in certain cases. This is not as powerful as completely global CSE, but not as slow either.

- **-frerun-cse-after-loop** Re-run common subexpression elimination after loop optimizations has been performed.

- **-fexpensive-optimizations** Perform a number of minor optimizations that are relatively expensive.

- **-fdelayed-branch** If supported for the target machine, attempt to reorder instructions to exploit instruction slots available after delayed branch instructions.

- **-fschedule-insns** If supported for the target machine, attempt to reorder instructions to eliminate execution stalls due to required data being unavailable. This helps machines that have slow floating point or memory load instructions by allowing other instructions to be issued until the result of the load or floating point instruction is required.
Loop Transformations

Sometimes loops can be transformed to different forms that are faster.

\[
\begin{align*}
& \text{for } i := 1 \text{ to } 1000 \text{ do} \\
& \hspace{1em} \text{for } j := 1 \text{ to } 1000 \text{ do} \\
& \hspace{2em} x[i,j] := y[i,j]; 
\end{align*}
\]

This might be transformed to a single, linear loop:

\[
\begin{align*}
& \text{for } i := 1 \text{ to } 1000000 \text{ do } x[i] := y[i]; 
\end{align*}
\]

Then it might be generated as a block-move instruction. This is sometimes called \textit{loop fusion}.

\textit{Code motion} is moving code to a more favorable location, \textit{e.g.}, moving \textit{(hoisting)} invariant code out of loops:

\[
\begin{align*}
& \text{for } i := 1 \text{ to } 1000 \text{ do} \\
& \hspace{1em} x[i] := y[i] \times \sqrt{a}; 
\end{align*}
\]

The code \texttt{sqrt(a)} does not change within the loop, so it could be moved above the loop and its value reused.
Strip Mining

Getting effective performance from a multi-processor machine (i.e., getting speedup close to $n$ from $n$ processors) is a difficult problem.

For some matrix computations, analysis of loops and array indexes may allow “strips” of the array to be sent to different processors, so that each processor can work on its strip in parallel.

This technique is effective for a significant minority (perhaps 25%) of important matrix computations.
Induction Variable Transformation

Some compilers transform the *induction variable* (loop index) to allow simplified subscripting expressions:

\[
\begin{align*}
\text{(:= I 1)} \\
\text{(LABEL 1)} \\
\text{(IF (<= I 1000)} \\
\quad \text{(PROGN \ldots (AREF X (+ -8 (* 8 I)))} \\
\quad \text{(:= I (+ I 1))} \\
\quad \text{(GOTO L1))})
\end{align*}
\]

might be transformed to:

\[
\begin{align*}
\text{(:= I’ 0)} \\
\text{(LABEL 1)} \\
\text{(IF (<= I’ 7992)} \\
\quad \text{(PROGN \ldots (AREF X I’)} \\
\quad \text{(:= I’ (+ I’ 8))} \\
\quad \text{(GOTO L1))})
\end{align*}
\]

Note that the loop index has no meaning outside the loop and may not have storage assigned to it. Some machines can automatically increment an index register after it is used (called *postincrement*).
Finite Differencing

Finite differencing\(^{46}\) is a general technique for optimizing expensive computations \(f(i)\) that occur in a loop:

- Maintain local variables that hold previous values of the expensive computation \(f(i)\) and perhaps some auxiliary values.

- Incrementally compute a new value \(f(i + \delta)\) using:
  - the previous value \(f(i)\)
  - a difference from \(f(i)\).

Example: \(f(i) = i^2\)

<table>
<thead>
<tr>
<th>(i)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i^2)</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>9</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>first difference:</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>second difference:</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{46}\)Paige, R. and Koenig, S., “Finite Differencing of Computable Expressions”, *ACM Transactions on Programming Languages and Systems*, vol. 4, no. 3 (July 1982), pp. 402-454
Example: Computing Squares

Assume that multiplication is expensive. Consider the problem of computing squares of successive integers.

```
for i := 0 to 99 do
  x[i] := i*i;
```

versus

```
next := 0;
delta := 1;
for i := 0 to 99 do
  begin
    x[i] := next;
    next := next + delta;
    delta := delta + 2
  end;
```

The second version has more code, but does no multiplication.

This form of computation has a long history; it was the basis of Babbage’s Difference Engine.
General Case

Given an expression $f(x_1, ..., x_n)$, create a variable $E$ to hold its value.

- **Initialize:** Create code

  $$E = f(x_{10}, ..., x_{n0})$$

  to establish $E$ for the initial values of its arguments.

- **Derivative:** Replace each statement $dx_i$ that modifies some variable $x_i$ of $E$ by the statements:

  $$\partial^- E\langle dx_i \rangle$$
  $$dx_i$$
  $$\partial^+ E\langle dx_i \rangle$$

- **Redundant Code Elimination:** replace each occurrence of $f(x_1, ..., x_n)$ by $E$.

- **Dead Code Elimination:** remove any code that is now unused.
Finite Differencing for Set Operations

Finite differencing can be especially useful in optimizing set operations. Consider the following expression that is used in solving the “k queens” problem:\(^{47}\)

\[ i \notin \text{range}(\text{part}\_\text{sol}) \land i \in \{1..k\} \]

This can be transformed to:

\[ i \in \text{setdiff}\{(1..k), \text{part}\_\text{sol}\} \]

A variable \textit{unoccupied\_rows} can be introduced for this expression. Its initial value is the set \{1..k\}.

An update to \textit{part\_sol} (by recursive call),

\[ \text{part}_\text{sol} = \text{append}(\text{part}_\text{sol}, i) \]

leads to a corresponding change to \textit{unoccupied\_rows}

\[ \text{unoccupied\_rows} = \text{unoccupied\_rows} - \{i\} \]

This incremental update may be much cheaper than doing the original range computation or set difference every time.

Memoization

*Memoization* (or *memorization*) is the technique of saving previously calculated values of an expensive function $f(x)$. If a new request to compute $f(x)$ uses a value $x$ that was used previously, the value of $f(x)$ can be retrieved from a table faster than it could be recomputed.

Compare:

- caching
- common subexpression elimination

Advanced CPU’s may implement some memoization in hardware: if the CPU can determine that a computation has already been done and exists in a register, it can reuse the result.
Hardware Assistance

Hardly anyone writes programs in assembly language now. The performance of a computer depends on both the hardware and the compiler.

Hardware assistance can greatly improve performance for some expensive program operations:

- subroutine call
- array references
- matrix operations, graphics

Hardware designers increasingly rely on compilers to handle things that used to be done by hardware (e.g. delaying use of a result until it is ready), allowing CPU’s to run faster.
PowerPC Features

The PowerPC has several features that the compiler can use to improve the performance of generated code:

- **Store-multiple instruction**: makes saving registers faster, speeding up subroutine call.
- **Multiple condition-code registers**: better code can be generated for compound tests.
- **Cache prefetch instruction**: allows the CPU to start fetching memory before it is needed, avoiding cache miss delays.
- **Superscalar architecture**: 3 units (integer, float, branch) can execute simultaneously.
- **Out-of-order execution**: the processor can look ahead in the instruction stream for an instruction to execute. The compiler may move instructions to maximize this effect.
- **Conditional branch instructions** can indicate the “expected” outcome (branch or not branch). The processor can speculatively execute instructions in the expected path.
SPARC Features

The SPARC architecture has features that improve the performance of generated code:

• *Register windows*, a stack frame of integer registers on a CPU register stack, greatly improve the speed of subroutine call. A register window is divided into sections: Input, Local, and Output registers. When a subroutine call is made, the Output registers of the caller become the Input registers of the callee.

  – Parameter transmission is easy: just load a parameter into an Output register
  – No need to save and restore integer registers, since the Local and Output registers are in a new part of the stack.
Hardware Trends

Trends in modern CPU architecture present new demands and opportunities for the compiler writer:

- Larger memories: expansion of code size is not as costly as before; might trade code size for speed.
- The compiler can coexist with the running program, for just-in-time compilation.
- High cost for cache misses: a cache miss can cause the CPU to stall (wait) for many execution cycles. Code may be reordered to avoid cache misses.
- Multiple processors: using the processors effectively (getting a speedup of $n$ from $n$ processors) is a difficult challenge. Strip mining may be used to send parts of loops (and memory) to different processors.
- Superscalar architecture: code may be re-ordered to take advantage of out-of-order and speculative execution.
- As number of transistors on chip increases, things that were software become hardware: math subroutines, message passing, memoization, dynamic optimization.
Object-oriented Programming

Object-oriented programming (OOP) originated in the SIMULA language (1967) for discrete event simulation. The desire was to simulate large numbers of similar objects in an efficient manner. A class-instance representation achieves this goal.

- **Class**: represents the *behaviors* that are shared by all of its instances. Behaviors are implemented by *methods*.

- **Instance**: represents the data for a particular individual.

Classes are arranged in a hierarchy or *ontology*, with inheritance of methods from higher classes.
Access to Objects

Access to objects is accomplished by sending messages to them.

- Retrieving data values:
  \[(\text{send obj } x) \quad \text{or} \quad \text{obj.get}(X)()\]

  If \( x \) is a private data field, \( \text{get}(X)() \) is called an accessor or getter method.

- Setting data values:
  \[(\text{send obj } x: \ 3) \quad \text{or} \quad \text{obj.set}(X)(3)\]

  If \( x \) is a private data field, \( \text{set}(X)() \) is called a mutator or setter method.

- Requesting actions:
  \[(\text{send obj } \text{print}) \quad \text{or} \quad \text{obj.print}()\]

A message or method call is like a function call, but \textit{which} function is called depends on the runtime type (class) of the object.

Wrapping access to a field in accessor methods helps \textit{information hiding}, but hurts efficiency.
Domain Analysis

A domain analysis in English suggests an object decomposition:

- nouns correspond to objects or variables
- verbs correspond to methods
- adjectives correspond to attributes

An *ontology*, the set of things that exist, is represented by the class hierarchy.

Some have contrasted imperative programming (*subject* oriented) with OOP.
Internal Implementation is Hidden

Messages define a standard interface to objects. Objects may have different internal implementations as long as the message interface is maintained. If access is controlled via messages, OOP facilitates information hiding: application programs do not know and cannot depend on the internal implementation of the object.

Example: Vector (send v x) or v.getX()

- Vector type 1: x is stored.

- Vector type 2: r and theta are stored. x is computed as r * cos(theta)

The two kinds of vectors appear the same to the outside world.
Encapsulation with OOP

Object-oriented programming provides *encapsulation*: an external *interface* to an object in terms of messages is defined, but the internal implementation of the object is hidden.

**Modularity:** Objects are often a good way to think about the application domain.

**Modifiability:** The internal implementation of an object can be changed without modifying any other programs, as long as the external interface is maintained.

**Expandability:** New kinds of objects can be added to an existing system, as long as they present the same interface as existing objects.

To maintain encapsulation, it is good to make all accesses into messages, avoiding all direct accesses to instance variables: `obj.getX()` instead of `obj.x`  

- Hides distinction between what is computed and what is stored.
- Improves reusability and maintainability.
- May hurt performance.
Object-oriented Programming Terminology

- **Object**: typically refers to an instance (although classes may be objects too).

- **Class**: a description of a set of similar objects, the instances. This description typically includes:
  
  - *Instance variable* descriptions: the names and types of variables that are assumed to be defined for every subclass or instance of the class.
  
  - *Methods*: mapping from the *selector* or abstract name of the method to the specific function that implements the method for the class.

    
    ```
    draw:    circle_draw()
    ```

- **Instance**: an individual member of a class. Typically an instance is a member of exactly one class. An instance is a record that:

  - can be identified as being an object
  
  - denotes the class to which the object belongs
  
  - contains the instance variables

- **Superclass**: a class to which a given class belongs. Sometimes a class may have more than one superclass.
Terminology ...

- **Message:** an indirect procedure call. A message is sent to an instance object. The message contains a selector and optional arguments. The selector is looked up in the class of the object (or one of its superclasses) to find the method that implements the message. That method is called with the object to which the message was sent as its first argument (called `self`, or `this` in Java).

- **Selector:** the name of a message. A generic procedure name, e.g. `draw`, that could apply to various kinds of objects.

- **Method:** the procedure that implements a message. Often the name of a method is the class name combined with the selector, *e.g.* `square_draw`. 
Implementation of Objects

An object is basically just a record, with a bit of extra information:

- A tag to identify the record as an object. It may be more efficient to tag the class, eliminating the need to tag each object; if the language is strongly typed, runtime tags may not be needed.

- The class of the object: a pointer to the class data structure.

- The instance variables of the object.

If an object contains a lot of data, the overhead of the extra information is modest. However, for simple data such as Integer, the overhead is significant.

Allocation of space in an object and access to instance variables are the same as for records.
Are Basic Types Objects?

There is an advantage of consistency if basic types such as `integer` and `real` are objects. However:

- A boxed number requires more storage. (16 bytes for Java `Integer` vs. 4 bytes for `int`.)
- A statement `i = i + 1` requires allocating a new object (and garbage collecting the old one): a significant performance penalty.

Lisp encodes small integers as special pointer values, eliminating the need to box small integers; reals are boxed.

Java caches and reuses small `Integer` values from -128 to 127.

An alternative is to have both boxed and unboxed numbers; this improves performance but results in an inconsistent type system. Java uses this method; as a result, a generic method that does comparison, such as sorting, may have to be recoded 6 times to handle different types (`< vs. .compareTo()`).
Inheritance and Class Structure

OOP allows subclasses to *extend* a class, both in terms of instance variables and methods.

A common practice it to let subclasses *add* instance variables; the subclass inherits all instance variables of its parent.

- Subclasses simply add variables to the end of the record.
- Methods inherited from a superclass are guaranteed to work, since all needed instance variables will be available at the same constant offsets from the beginning of the record.
- It is not possible to change an object from a superclass to one of its subclasses, since that would increase its size after it is allocated.

*Multiple inheritance* could cause problems of inconsistent offsets or name conflicts.
Message Sending

Sending a message is just a function call. However, the function (method) that is called is determined dynamically by the runtime type of the object to which the message is sent.

```
Drawable
  /     \
 /       \
Circle    Square
draw: circle_draw()   draw: square_draw()
```

Suppose we execute: `obj.draw(x,y)`

1. Find the method corresponding to the message selector. Since `obj` is a `circle`, `draw` is looked up as `circle_draw()`.

2. Assemble the arguments:
   `obj.draw(x,y)` becomes `circle_draw(obj,x,y)`.
   `obj` is the (hidden) `this` argument of the function.

3. Call the method function with the arguments as usual.
Dynamic Method Lookup

Each class associates a selector with the method that implements the selector for that class:

```lisp
((area circle_area) (draw circle_draw) ...)
```

A typical dynamic method lookup procedure is:

- Look for the selector in the class of the object to which the message was sent.
- If it is not found, look in superclasses of the class.

The first method found in this search up the class tree is the one that is used. This provides:

- **shadowing**: a more specific subclass method overrides a superclass method with the same name.
- **inheritance**: methods of a superclass are inherited by its subclasses.
Static Method Lookup

In a static language, all of the methods defined for each class can be determined at compile time. Lookup of the called routine can then be done efficiently:

- Selector names are converted to integer offsets.
- A class is implemented during execution as an array of method addresses.
- A method call `obj.sel(args)` is executed by:
  - Getting the class pointer from `obj`
  - Using the offset associated with `sel` to look up the method address in the method table of the class
  - Calling the method.

This takes only a few instructions more than an ordinary function call. This technique is used in C++. 
Multiple Inheritance

Multiple inheritance means that a class can have multiple superclasses and inherit from them.

Multiple inheritance can cause several problems:

- Name conflicts of instance variables.
- Methods with the same name from multiple parents.
- Instance variables no longer have simple constant offsets.

Variations of inheritance include:

- Using types of all arguments (not just the first) to determine the method (CLOS)
- Method Combination (Flavors): the methods of multiple parents can be combined, e.g. a window with border and title.
- SendSuper (Loops): a more specialized subclass method can call the parent method. Useful e.g. to assign serial numbers to manufactured objects.
Improving OOP Efficiency

• Use table lookup (array of method addresses) to make method lookup fast (C++).

• Cache selector and method at lowest class level to avoid search (Self).

• Compile specialized methods “just in time” (JIT) when first used:
  – method calls can be converted to function calls when the class is known
  – small methods such as obj.getX() can be compiled in-line
  – partial evaluation may improve efficiency
Smalltalk
Smalltalk Code

| minLength i j | 

minLength := self length.

100 timesRepeat:
[i := ((Float random * self size) truncate + 1) asInteger.
  j := ((Float random * self size) truncate + 1) asInteger.
  self exchange: i and: j.
  self length < minLength
  ifTrue: [minLength := self length]
  ifFalse: [self exchange: i and: j]]
ThingLab

ThingLab\textsuperscript{48} is an interactive graphical simulation system based on Smalltalk.

- Objects have ports that can be connected graphically.
- If an object is modified interactively, it propagates changes to its ports, and thus to objects to which it is connected.
- Features of objects can be “anchored” to prevent them from changing.
- An object may do search by attempting to change different port values to make itself consistent.
- Problems are solved by value propagation or by relaxation.

ThingLab Examples
Good Features of OOP

- Encapsulation: implementations of objects can be modified without modifying clients. (However, it might change performance.)
- Data types and related procedures are grouped.
- Polymorphism: some generic methods can be reused effectively.
- Inheritance: methods can be inherited within a hierarchy.
Unfortunate Features of OOP

• OOP tends to require that everything be objects. Hard to use with existing systems.

• Reusing generic procedures is not easy:
  – Programmer must know method name and arguments.
  – Arguments must respond appropriately to all messages that may be sent to them by the method or anything it calls.
  – Methods may produce unexpected and unwanted side-effects.

• Slow in execution.
  – Method lookup overhead
  – Opacity of objects prevents optimization across messages.
  – A layered object structure compounds the problem.

Some OOP systems “succeed” but have to be discarded and rewritten for efficiency.

• System structure becomes baroque and hard to change (just the opposite of what is advertised).
Why OOP Is Not Enough

- OOP requires the programmer to know too many details about object and method names and implementations.

- OOP requires application data to conform to conventions of the generic procedures:
  - OOP requires an object to be a member of a class rather than be viewable as a member.
  - Some OOP systems automatically include slots of supers in all their descendants. This inhibits use of different representations.
  - An object cannot be a member of a class in more than one way. (A pipe is a circle in two ways.)
  - No single definition of an object is likely to encompass all possible uses (or if it did, it would be too big for typical uses).

- Responsibility for a task may be split across many classes.

- OOP is often slow in execution.

- OOP doesn’t play well with relational databases.
Top Ten Lies About OOP

10. Objects are good for everything.

9. Object-oriented software is simpler.
   (No: everything is a server, and servers are harder to write.)

8. Subclassing is a good way to extend software or libraries.

7. Object-oriented toolkits produce interchangeable components.
   (No: you get components the size of a nuclear aircraft carrier, with
    internal interfaces that are too complex to duplicate.)

6. Using object-oriented programming languages helps build object-oriented systems.

5. Object-oriented software is easier to evolve.
   (No: jigsaw-puzzle modularity is a serious problem.)

4. Classes are good for modularity.
   (No: most worthwhile modules have more than one class.)

3. Reuse happens.
   (No: you have to work too hard to make it possible. He distinguished
    between *use*, exploiting existing code, and *reuse*, building new
    code by extending existing code.)

2. Object-oriented software has fewer bugs.
   (No: it has different bugs.)

1. C++ is an object-oriented programming language.

---

49 From a keynote talk at the June 1993 Usenix conference by Mike Powell of Sun Labs, who is working
on an object-oriented operating system in C++ (as recorded by Henry Spencer in the July 1993 issue of
"login:" magazine, whose remarks are in parentheses.)
Aspect-Oriented Programming

*Aspect-Oriented Programming*\(^50\) is intended to facilitate coding of *cross-cutting* aspects, i.e. those aspects that cut across a typical decomposition of an application in terms of object classes:

- Error handling
- Memory management
- Logging

In Aspect-Oriented Programming, an *aspect weaver* combines program fragments from separate aspects of a design at *cut points* or *join points*.

- **Adv:** Code for the aspect can be described in one place, making it easy to change.

- **Dis:** Combination of source code from different places violates modularity.

AspectJ is an aspect-oriented system for Java.

Lisp

Lisp facilitates the manipulation of symbolic expressions such as program code. Therefore, Lisp is ideal for advanced compilation techniques that involve transformation of code.

Greenspun’s Tenth Rule of Programming:

Any sufficiently complicated C or Fortran program contains an ad hoc informally-specified bug-ridden slow implementation of half of Common Lisp.

Example:

<table>
<thead>
<tr>
<th>Language</th>
<th>Lines:</th>
<th>Time:</th>
<th>Personnel:</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>C++</td>
<td>25,000</td>
<td>10 years</td>
<td>Ph.D.</td>
<td>$2,000,000</td>
</tr>
<tr>
<td>Lisp</td>
<td>150</td>
<td>1 week</td>
<td>Undergrad</td>
<td>$200</td>
</tr>
</tbody>
</table>
History of Lisp

Lisp was invented in the late 1950’s and early 1960’s at M.I.T. by John McCarthy. Lisp is based in part on the Lambda Calculus, a mathematical formalism developed by Alonzo Church (1903-1995).

Lisp is the second-oldest language still in widespread use (the oldest is Fortran).

Lisp is especially used for work in Artificial Intelligence. It is also an ideal language for advanced work in compilers.

Scheme is a small, simple dialect of Lisp. Common Lisp is a larger, standardized dialect of Lisp with many features. Clojure is a Lisp dialect based on Java.
Advantages of Lisp

- **Recursion:** A program can call itself as a subroutine.
- **Dynamic Type Checking:** types are tested at runtime
  - Allows short, elegant, powerful programs
  - Incurs a performance penalty
- **Garbage Collection:** Data storage is recycled automatically.
- **Uniform Representation:** Programs and data have the same form.
  - Programs can examine other programs.
  - Programs can write programs.
  - Programs can modify themselves (learn).
  - Data structures can contain programs.
- **Interaction:** The user can combine program writing, compilation, testing, debugging, running in a single interactive session.
Lisp Interaction

The *Lisp Interpreter* interacts with the user:

1. Read an expression from the terminal.
2. Evaluate the expression to determine its value.
3. Print the value; go to step 1.

This is sometimes called the *read-eval-print loop*.

The interpreter prints a *prompt*, which is > in GCL 51.

```plaintext
% lisp
>57
57

>(+ 32 57)
89

>(+ (* 8 4) (- 60 3))
89

> (sqrt 2)
1.4142135623730951
```

---

51 Gnu Common Lisp. Originally developed at the University of Kyoto as Kyoto Common Lisp or KCL, it was enhanced by Prof. Bill Schelter at UT to become Austin Kyoto Common Lisp or AKCL, later renamed GCL. To exit GCL, enter *(bye)*. To get out of an error break, enter :q or :h for help.
Function Definition

Functions are defined using `defun` (define function):

```lisp
(defun myabs (x)
  (if (>= x 0)
      x
    (- x))
)
```

```lisp
> (myabs 3)
3
```

```lisp
> (myabs -7)
7
```

Local variables can be declared using `let`. Variables can be assigned values using `setq` (set-quote):

```lisp
(defun cylinder-volume (radius height)
  (let (area)
    (setq area (* pi (expt radius 2)))
    (* area height)))
```
List Structure

**cons:** first | rest

Lists are a basic data structure in Lisp; in fact, Lisp code is made of lists. The external (printed) representation of lists is a sequence of elements enclosed in parentheses.

\[
\begin{align*}
(\text{first } '(a \ b \ c)) & = A \\
(\text{rest } '(a \ b \ c)) & = (B \ C) \\
(\text{second } '(a \ b \ c)) & = B \\
(\text{cons } 'z \ '(a \ b \ c)) & = (Z \ A \ B \ C) \\
(\text{list } 'a \ 'b \ 'c) & = (A \ B \ C)
\end{align*}
\]

*first* is also called *car*; *rest* is also called *cdr*.

The quote symbol ’ is a shorthand for the pseudo-function *quote*. \((\text{quote } x) = x\), that is, quote returns the argument itself rather than evaluating the argument.
We consider the fundamental form of a program to be the *abstract syntax tree* (AST) – not source code.

Lisp code is already in AST form, and Lisp is ideal for implementing program generation and transformation. It is easy to generate code in ordinary programming languages from Lisp.
Binding Lists

A binding is a correspondence of a name and a value.

A set of bindings is represented as a list, called an association list, or alist for short. A new binding can be added by:

\[
\text{(push (list name value) binding-list)}
\]

A name can be looked up using assoc:

\[
\text{(assoc name binding-list)}
\]

\[
\text{(assoc '?y '((?x 3) (?y 4) (?z 5))) = (?Y 4)}
\]

The value of the binding can be gotten using second:

\[
\text{(second (assoc '?y '((?x 3) (?y 4) (?z 5))) = 4)}
\]
Substitution

(subst x y z) ("substitute x for y in z") can be used to make new code from a pattern.

>(subst pi 'pi '(* pi (* r r)))
(* 3.14159265 (* R R))

>(subst 1 'i '(aref x (+ -8 (* 8 i))))
(AREF X (+ -8 (* 8 1)))

(sublis alist form) makes multiple substitutions:

> (sublis '((rose . peach) (smell . taste))
    '(a rose by any other name
       would smell as sweet))
(A PEACH BY ANY OTHER NAME WOULD TASTE AS SWEET)
(defun copy-tree (z)
  (if (consp z)
      (cons (copy-tree (first z))
            (copy-tree (rest z)))
      z))

; substitute x for y in z
(defun subst (x y z)
  (if (consp z)
      (cons (subst x y (first z))
            (subst x y (rest z)))
      (if (eql z y) x z))

; substitute in z with bindings in alist
(defun sublis (alist z)
  (let (pair)
    (if (consp z)
        (cons (sublis alist (first z))
              (sublis alist (rest z)))
        (if (setq pair (assoc z alist))
            (cdr pair)
            z))))

These are system functions in Common Lisp. The system functions subst and sublis copy only as much structure as necessary.
Substitution in C

/* Substitute new for old in tree */
TOKEN subst (TOKEN new, TOKEN old, TOKEN tree)
{
    TOKEN tok, last, opnd, ptr;
    if (tree == NULL) return (tree);
    if (tree->tokentype == OPERATOR)
    {
        last = NULL;
        ptr = tree->operands;
        tok = copytok(tree);
        while ( ptr != NULL )
        {
            opnd = subst (new, old, ptr);
            if (last == NULL)
                tok->operands = opnd;
            else last->link = opnd;
            last = opnd;
            ptr = ptr->link;
        }
        return (tok) ;
    }
    else if (tree->tokentype == IDENTIFIERTOK
        && strcmp(tree->stringval,
                   old->stringval) == 0)
        return ( copytok(new) );
    else return ( copytok(tree) );
}
Loop Unrolling

Substitution makes it easy to do loop unrolling:

(defun unroll (var n code)
  (let (res)
    (dotimes (i n)
      (push (subst (1+ i) var code) res))
    (cons 'progn (reverse res))) )

>(unroll 'j 5 '(|:=| (aref x (+ -8 (* 8 j))) 0))

(PROGN
  (|:=| (AREF X (+ -8 (* 8 1))) 0)
  (|:=| (AREF X (+ -8 (* 8 2))) 0)
  (|:=| (AREF X (+ -8 (* 8 3))) 0)
  (|:=| (AREF X (+ -8 (* 8 4))) 0)
  (|:=| (AREF X (+ -8 (* 8 5))) 0)))
Instantiating Design Patterns

sublis can instantiate design patterns. For example, we can instantiate a tree-recursive accumulator pattern to make various functions:

(setq pattern
  '(defun ?fun (tree)
    (if (consp tree)
        (?combine (?fun (car tree))
          (?fun (cdr tree)))
        (if (?test tree) ?trueval ?falseval))))

>(sublis '((?fun . nnums)
               (?combine . +)
               (?test . numberp)
               (?trueval . 1)
               (?falseval . 0)) pattern)

(DEFUN NNUMS (TREE)
  (IF (CONSP TREE)
      (+ (NNUMS (CAR TREE))
          (NNUMS (CDR TREE)))
      (IF (NUMBERP TREE) 1 0)))

>(nnums ’(+ 3 (* i 5)))
2
Pattern Matching

Pattern matching is the inverse of substitution: it tests to see whether an input is an instance of a pattern, and if so, how it matches. 53

```
(match '(defun ?fun (tree)
  (if (consp tree)
      (?combine (?fun (car tree))
          (?fun (cdr tree)))
      (if (?test tree) ?trueval ?falseval))
  '(DEFUN NNUMS (TREE)
      (IF (CONSP TREE)
          (+ (NNUMS (CAR TREE))
              (NNUMS (CDR TREE)))
          (IF (NUMBERP TREE) 1 0))))

((?FALSEVAL . 0) (?TRUEVAL . 1) (?TEST . NUMBERP)
  (?COMBINE . +) (?FUN . NNUMS) (T . T))

(match '(- ?x (- ?y))
  '(- z (- (* u v))))

((?Y * U V) (?X . Z) (T . T))
```

53 The pattern matcher code can be loaded using (load "/projects/cs375/patmatch.lsp").
Pattern Matching

(defun equal (pat inp)
  (if (consp pat) ; interior node?
    (and (consp inp)
      (equal (car pat) (car inp))
      (equal (cdr pat) (cdr inp))
      (eql pat inp)) ) ; leaf node

(defun match (pat inp) (matchb pat inp '((t . t))))
(defun matchb (pat inp bindings)
  (and bindings
    (if (consp pat) ; interior node?
      (and (consp inp)
        (matchb (cdr pat)
          (cdr inp)
          (matchb (car pat)
            (car inp) bindings)))
      (if (varp pat) ; leaf: variable?
        (let ((binding (assoc pat bindings)))
          (if binding
            (and (equal inp (cdr binding))
              bindings)
            (cons (cons pat inp) bindings)))
      (and (eql pat inp) bindings)) ) ) )
Transformation by Patterns

Matching and substitution can be combined to transform an input from a pattern-pair: a list of input pattern and output pattern.

(defun transform (pattern-pair input)
  (let (bindings)
    (if (setq bindings
      (match (first pattern-pair) input))
      (sublis bindings (second pattern-pair)))))

> (transform '( (- ?x (- ?y)) (+ ?x ?y))
  '(- z (- (* u v))) )

(+ Z (* U V))

> (transform '((- (+ ?x ?y) (+ ?z ?y))
  (- ?x ?z))
  '(- (+ (age tom) (age mary))
  (+ (age bill) (age mary))))

(- (AGE TOM) (AGE BILL))
Transformation Patterns

Optimization:

(defpatterns 'opt
  '( ((+ ?x 0) ?x)
      ((* ?x 0) 0)
      ((* ?x 1) ?x)
      ((:= ?x (+ ?x 1)) (incf ?x)))
)

Language translation:

(defpatterns 'lisptoc
  '( ((aref ?x ?y) "" ?x "[" ?y "]")
      ((incf ?x) "++" ?x))
      ((+ ?x ?y) "(" ?x " + " ?y ")")
      ((= ?x ?y) "(" ?x " == " ?y ")")
      ((and ?x ?y) "(" ?x " && " ?y ")")
      ((if ?c ?s1 ?s2) "if (" ?c ")
          \Return ?s1
          \Return ?s2))
)
Program Transformation using Lisp

>code
(IF (AND (= J 7) (<> K 3))
   (PROGN (= X (+ (AREF A I) 3))
         (= I (+ I 1)))
)

>(cpr (transform (transform code 'opt)
              'lisptoc))

if (((j == 7) && (k != 3)))
{
  x = (a[i] + 3);
  ++i;
}
Looping Patterns

((for ?i ?start ?end ?s)

(PROGN (\:= ?i ?start)
 (LABEL ?j)
 (IF (<= ?i ?end)
    (PROGN ?s
      (\:= ?i (+ 1 ?i))
      (GOTO ?j) )))

 t ((?j (gentemp "LABEL"))))

((while ?c ?s)

(PROGN (LABEL ?j)
 (IF ?c (PROGN ?s (GOTO ?j))))

 t ((?j (gentemp "LABEL"))))

((repeat-until ?c . ?s)

(PROGN (LABEL ?j)
 (progn . ?s)
 (IF ?c (PROGN) (GOTO ?j)))

 t ((?j (gentemp "LABEL"))))
Code Expansion by Looping Patterns

>(trans '(for i 1 100
    (\:= sum (+ sum (aref x (* 8 i)))))
  'loops)

(PROGN
  (\:=| I 1)
  (LABEL LABEL7)
  (IF (<= I 100)
    (PROGN
      (\:=| SUM (+ SUM (AREF X (* 8 I)))))
      (\:=| I (+ 1 I))
      (GOTO LABEL7))))

>(trans '(repeat-until (> i 100)
    (writeln i) (\:= i (+ i 1)))
  'loops)

(PROGN
  (LABEL LABEL8)
  (PROGN (WRITELN I) (\:=| I (+ I 1)))
  (IF (> I 100) (PROGN) (GOTO LABEL8))))
Multi-Level Patterns

(redefs patterns 'loop
  ((average ?set)
   (make-loop ?set ?item (?total ?n)
     (progn (setq ?total 0)
       (setq ?n 0))
     (progn (incf ?total ?item)
       (incf ?n))
     (/ ?total ?n) )
   t ((?item (gentemp "ITEM"))
     (?total (gentemp "TOTAL"))
     (?n (gentemp "N")))) ) ) )

(redefs patterns 'list
  '()
    (let (?ptr ?item . ?vars)
      ?init
      (setq ?ptr ?lst)
    (while ?ptr
     (setq ?item (first ?ptr))
     (setq ?ptr (rest ?ptr))
    ?action)
    ?result)
   t ((?ptr (gentemp "PTR")) ) ) )

Use of Multi-Level Patterns

(cpr (trans
  (trans
    (trans '(defun zb (x) (average x))
      'loop) 'list) 'lisptoc))

zb(x)
{
  int ptr30; int item27; int total28; int n29;;
  {
    total28 = 0;
    n29 = 0;
  };
  ptr30 = x;
  while ( ptr30 )
  {
    item27 = first(ptr30);
    ptr30 = rest(ptr30);
    {
      total28 += item27;
      ++n29;
    };
  }
  return ((total28 / n29));
};
Function Inlining

_Inlining_ is the expansion of the code of a function at the point of call. If the code says $\text{sqrt}(x)$, _sqrt_ can be invoked as a _closed_ function in the usual way, or it can be expanded as an _open_ or _inline_ function by expanding the definition of _sqrt_ at each point of call.

Inline expansion saves the overhead of subroutine call and parameter transmission; it may allow additional optimization because the compiler can now see that certain things (including types) are constant.

If code is in the form of abstract syntax trees, inlining is easy:

- Make sure the variables of the function are distinct from those of the caller.
- Generate assignment statements for the arguments.
- Copy the code of the function.
Program Transformation

Many kinds of transformations of a program are possible:

- Optimization of various kinds. Low-level inefficiencies created by a program generation system can be removed.
- Specialization. Generic operations or program patterns can be specialized to the form needed for a specific implementation of an abstract data structure. OOP methods can be specialized for subclasses.
- Language translation. Transformations can change code into the syntax of the target language.
- Code expansion. Small amounts of input code can be transformed into large amounts of output code. The expansion can depend on specifications that are much smaller than the final code.
- Partial evaluation. Things that are constant at compile time can be evaluated and eliminated from code.
- Changing recursion to iteration
- Making code more readable
- Making code less readable (code obfuscation)
Paul Graham:

“If you ever do find yourself working for a startup, here’s a handy tip for evaluating competitors. Read their job listings...

After a couple years of this I could tell which companies to worry about and which not to. The more of an IT flavor the job descriptions had, the less dangerous the company was. The safest kind were the ones that wanted Oracle experience. You never had to worry about those. You were also safe if they said they wanted C++ or Java developers. If they wanted Perl or Python programmers, that would be a bit frightening – that’s starting to sound like a company where the technical side, at least, is run by real hackers. If I had ever seen a job posting looking for Lisp hackers, I would have been really worried.”
English

English is a context-free language (more or less).

English has a great deal of ambiguity, compared to programming languages. By restricting the language to an *English subset* for a particular application domain, English I/O can be made quite tractable.

Some users may prefer an English-like interface to a more formal language.

Of course, the best way to process English is in Lisp.
Expression Trees to English

(defun op (x) (first x))
(defun lhs (x) (second x))
(defun rhs (x) (third x))

(defun op->english (op)
  (list 'the
       (second (assoc op '(+ sum)
                ( - difference)
                (* product)
                (/ quotient)
                (sin sine)
                (cos cosine))))') of)

(defun exp->english (x)
  (if (consp x) ; operator?
      (append
       (op->english (op x))
       (exp->english (lhs x))
       (if (null (cddr x)) ; unary?
           ()
           (cons 'and
                 (exp->english (rhs x)) )) ) )
    (list x)) ) ; leaf: operand
Generating English

%%lisp
>(load "/projects/cs375/expenglish.lsp")

>(exp->english 'x)

(X)

>(exp->english '+ x y))

(The sum of x and y)

>(exp->english '/ (cos z) (+ x (sin y))))

(The quotient of the cosine of z and the sum of x and the sine of y)

360
Parsing English

In most cases, a parser for a programming language never has to back up: if it sees if, the input must be an if statement or an error.

Parsing English requires that the parser be able to fail, back up, and try something else: if it sees in, the input might be in Austin or in April, which may be handled by different kinds of grammar rules.

Backup means that parsing is a search process, i.e. likely to be NP-complete. However, since English sentences are usually short, this is not a problem in practice.

An Augmented Transition Network (ATN) framework facilitates parsing of English.
• A global variable *sent* points to a list of words that is the remaining input sentence:
  (GOOD CHINESE RESTAURANT IN LOS ALTOS)

• A global variable *word* points to the current word:
  GOOD

• (cat category ) tests whether a word is in the specified category. It can also translate the word, e.g. (cat ’month) might return 3 if *word* is MARCH.

• (next) moves to the next word in the input

• (saveptr) saves the current sentence position on a stack.

• (success) pops a saved position off the stack and returns T.

• (fail) restores a saved position from the stack (restoring *sent* and *word*) and returns NIL.
Parsing Functions

The parser works by recursive descent, but with the ability to fail and back up and try another path.

(defun loc ()
  (let (locname)
    (saveptr)
    (if (and (eq *word* 'in) (next))
        (setq locname (cat 'city))
        (next))
    (progn
      (addrestrict
        (list 'equal
          (dbaccess 'customer-city)
          (kwote locname)))
      (success))
    (fail)))))
Grammar Compiler

It is easy to write a grammar compiler that converts a Yacc-like grammar into the equivalent ATN parsing functions. This is especially easy in Lisp since Lisp code and Lisp data are the same thing.

(rulecom '(LOC -> (in (city))
           (restrict 'customer-city $2)) )

(DEFUN LOC62 ()
  (LET ($1 $2)
    (SAVEPTR)
    (IF (AND (AND (EQL (SETQ $1 *WORD*) 'IN)
                   (NEXT))
           (SETQ $2 (CITY)))
      (PROGN (SUCCESS)
               (RErestrict 'CUSTOMER-CITY $2))
             (FAIL))))

56 file gramcom.lsp
Access to Database

English can be a good language to use query a database.

(deflexicon
  '((a/an   (a an some))
    (i/you  (i you one))
    (get    (get find obtain))
    (quality ((good 2.5) ))
    (restword (restaurant
                (restaurants restaurant))))
)

\[57\text{file restgram.lsp}\]
Restaurant Database Grammar

(defgrammar
  (s  ->  ((command) (a/an)? (qual)? (resttype)?
    (restword) (qualb)? (loc)?)
  (makequery (combine (retrieve 'restaurant)
    (retrieve 'streetno)
    (retrieve 'street)
    (retrieve 'rating)
    ($3 $4 $6 $7)))

  (s  ->  (where can (i/you) (get) (qual)?
    (resttype)? food ? (loc)?)
  (makequery (combine (retrieve 'restaurant)
    (retrieve 'streetno)
    (retrieve 'street)
    (retrieve 'rating)
    ($5 $6 $8)))

  (command  ->  (what is) t)
  (qual  ->  ((quality))
    (restrictb '>= 'rating $1))
  (qualb  ->  (rated above (number))
    (restrictb '>= 'rating $3))
  (resttype  ->  ((kindfood))
    (restrict 'foodtype $1))
  (loc  ->  (in (city)) (restrict 'city $2))
Restaurant Queries

%lisp
>(load "/projects/cs375/restaurant.lsp")

>(askr '(where can i get ice cream in berkeley))

((2001-FLAVORS-ICE-CREAM-&-YOGUR 2485 TELEGRAPH-AVE)
 (BASKIN-ROBBINS 1471 SHATTUCK-AVE)
 (DOUBLE-RAINBOW 2236 SHATTUCK-AVE)
 (FOSTERS-FREEZE 1199 UNIVERSITY-AVE)
 (MARBLE-TWENTY-ONE-ICE-CREAM 2270 SHATTUCK-AVE)
 (SACRAMENTO-ICE-CREAM-SHOP 2448 SACRAMENTO-ST)
 (THE-LATEST-SCOOP 1017 ASHBY-AVE))

>(askr '(show me chinese restaurants rated above 2.5 in los altos))

((CHINA-VALLEY 355 STATE-ST)
 (GRAND-CHINA-RESTAURANT 5100 EL-CAMINO-REAL)
 (HUNAN-HOMES-RESTAURANT 4880 EL-CAMINO-REAL)
 (LUCKY-CHINESE-RESTAURANT 140 STATE-ST)
 (MANDARIN-CLASSIC 397 MAIN-ST)
 (ROYAL-PALACE 4320 EL-CAMINO-REAL))
(deflexicon
  '((propname (radius diameter circumference
               area volume height velocity time
               weight power height work speed mass))
    (a/an    (a an))
    (the/its (the its))
    (objname (circle sphere fall lift)))
) ; deflexicon

(defgrammar
  (s    -> (what is (property) of (object))
         (list 'calculate $3 $5))
  (property -> ((the/its)? (propname)) $2)
  (quantity -> ((number)) $1)
  (object    -> ((a/an)? (objname) with (objprops))
               (cons 'object (cons $2 $4)))
  (objprops -> ((objprop) and (objprops))
              (cons $1 $3))
  (objprops -> ((objprop)) (list $1))
  (objprop  -> ((a/an)? (propname) of ? (quantity)
                (cons $2 $4))
  (objprop  -> ((propname) = (quantity))
                (cons $1 $3))

  \footnote{file physgram.lsp}
Physics Queries

\[\text{%lisp}
\]
\>$\text{(load "}[/\text{projects/cs375/physics.lsp}])$
\>$\text{(phys ' (what is the area of a circle with diameter = 10))}$

78.539816339744831

\>$\text{(phys ' (what is the circumference of a circle with an area of 100))}$

35.449077018110316

\>$\text{(phys ' (what is the power of a lift with mass = 100 and height = 6 and time = 10))}$

588.399