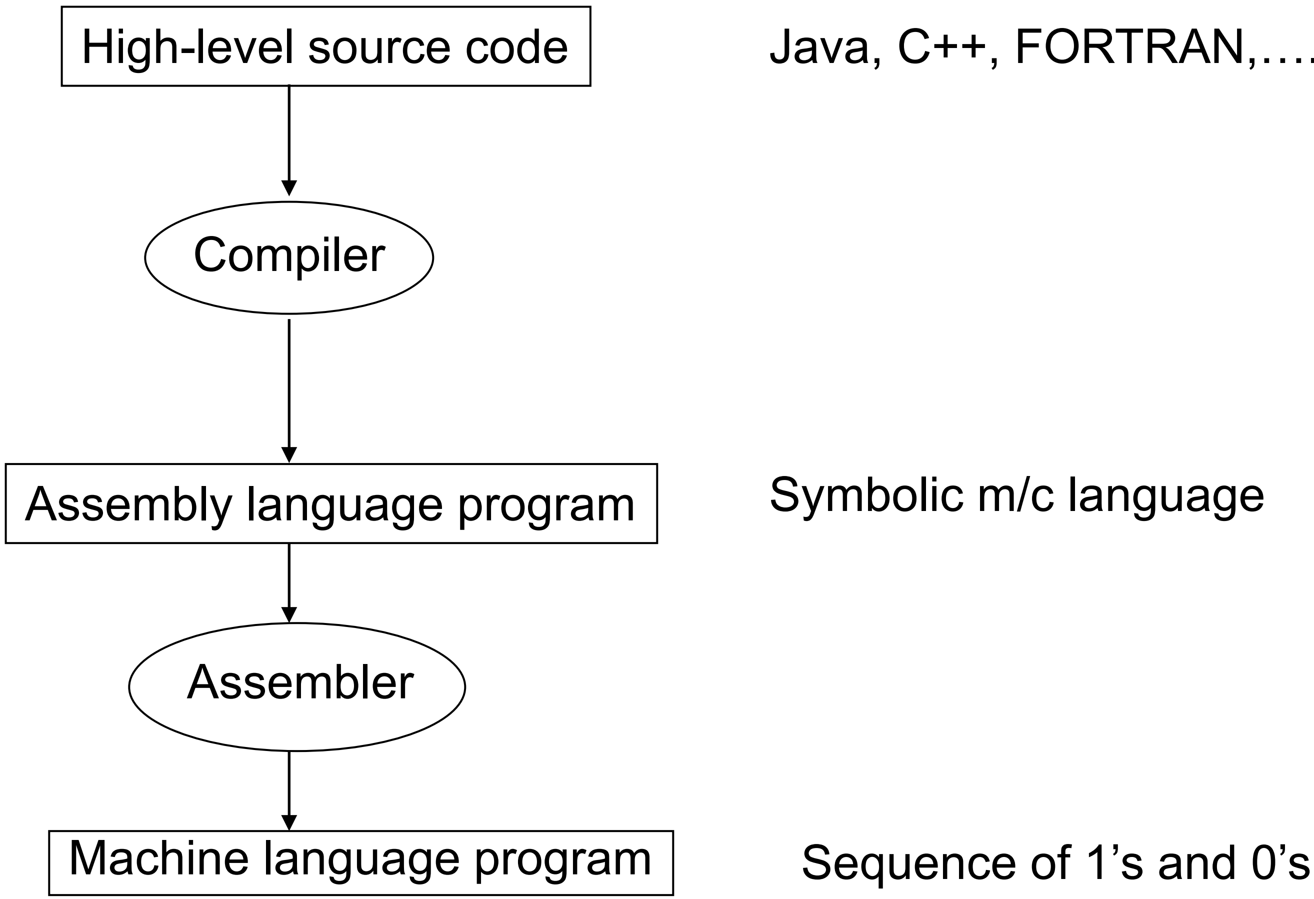
Introduction to
x86 ISA and Compilers

High-level Structure of Compiler



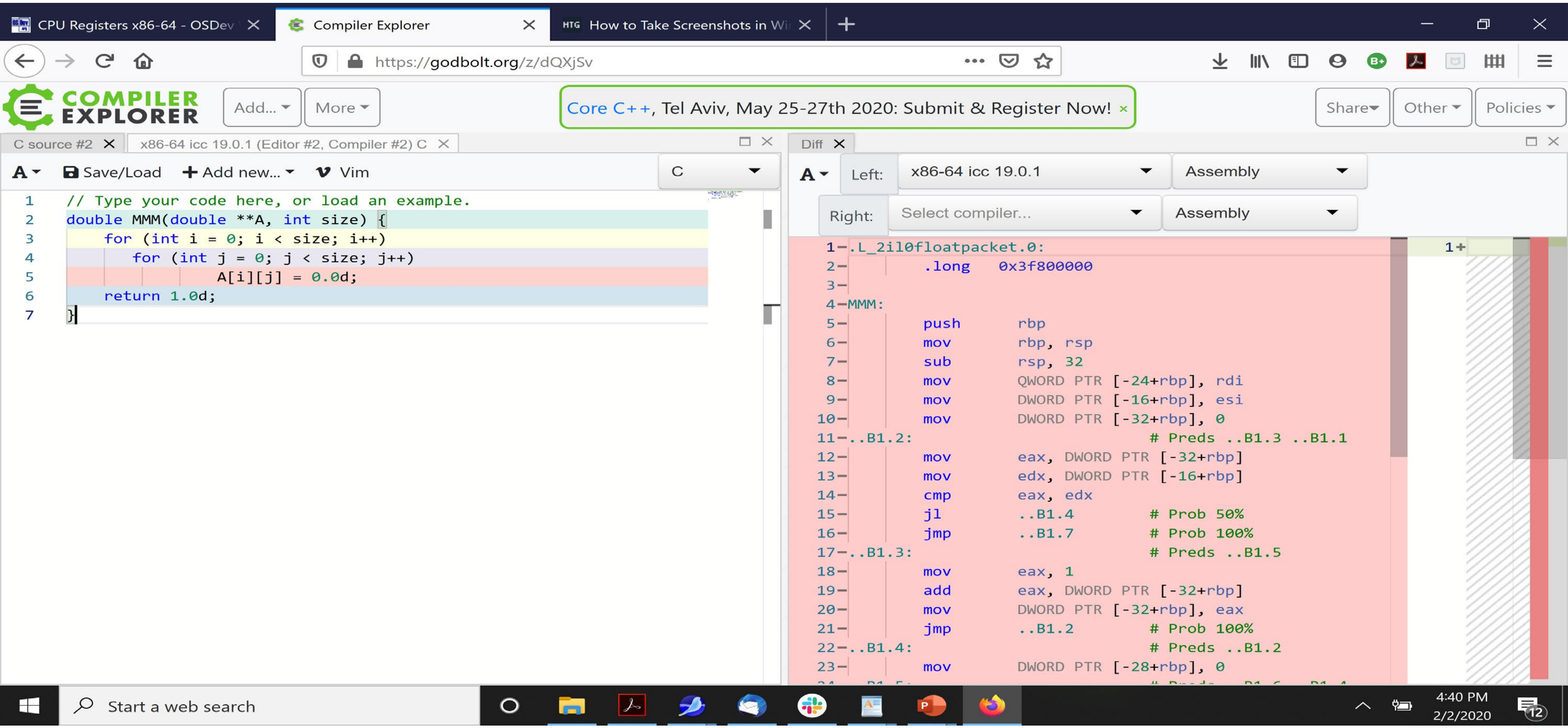
There may be different assembly languages for the same ISA.
Example: AT&T (used by gcc) and Intel (used by icc) formats for x86 ISA.

x-86 instruction set

- x-86 ISA is very complex
  - CISC instruction set
  - Evolved over time:
    - 16 bit → 32 bit → 64 bit
    - MMX vector instructions
  - Assembly format: AT&T format and Intel format
- We will focus on x86-32 bit ISA since it is easier to understand
- Once you figure this out, x86-64 bit ISA is not hard

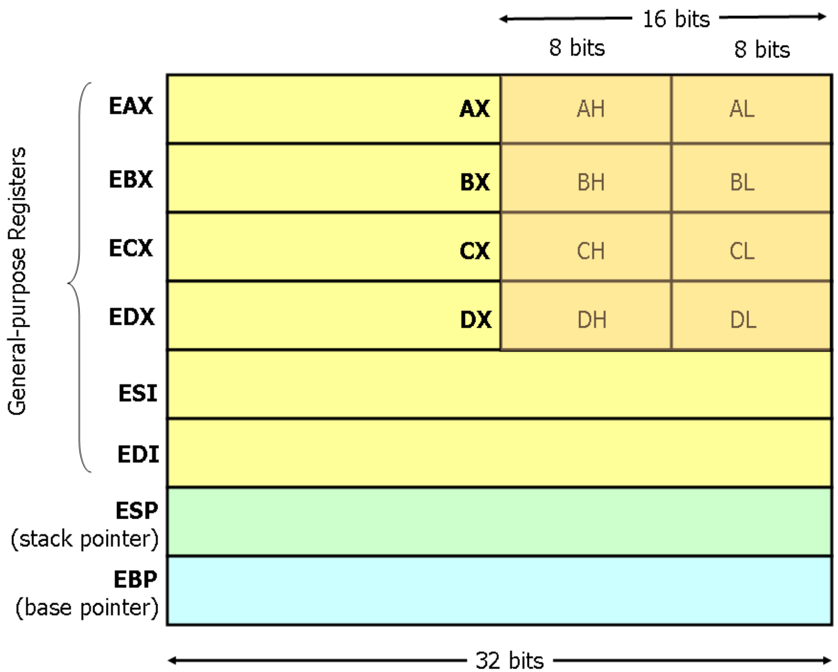
Useful website

- https://godbolt.org/



X86-32 Quick Overview

- Registers:
  - General purpose 32bit: eax, ebx, ecx, edx, esi, edi
    - Also 16-bit: ax, bx, etc., and 8-bit: al, ah, bl, bh, etc.
  - Special registers:
    - esp: stack pointer
    - ebp: frame base pointer



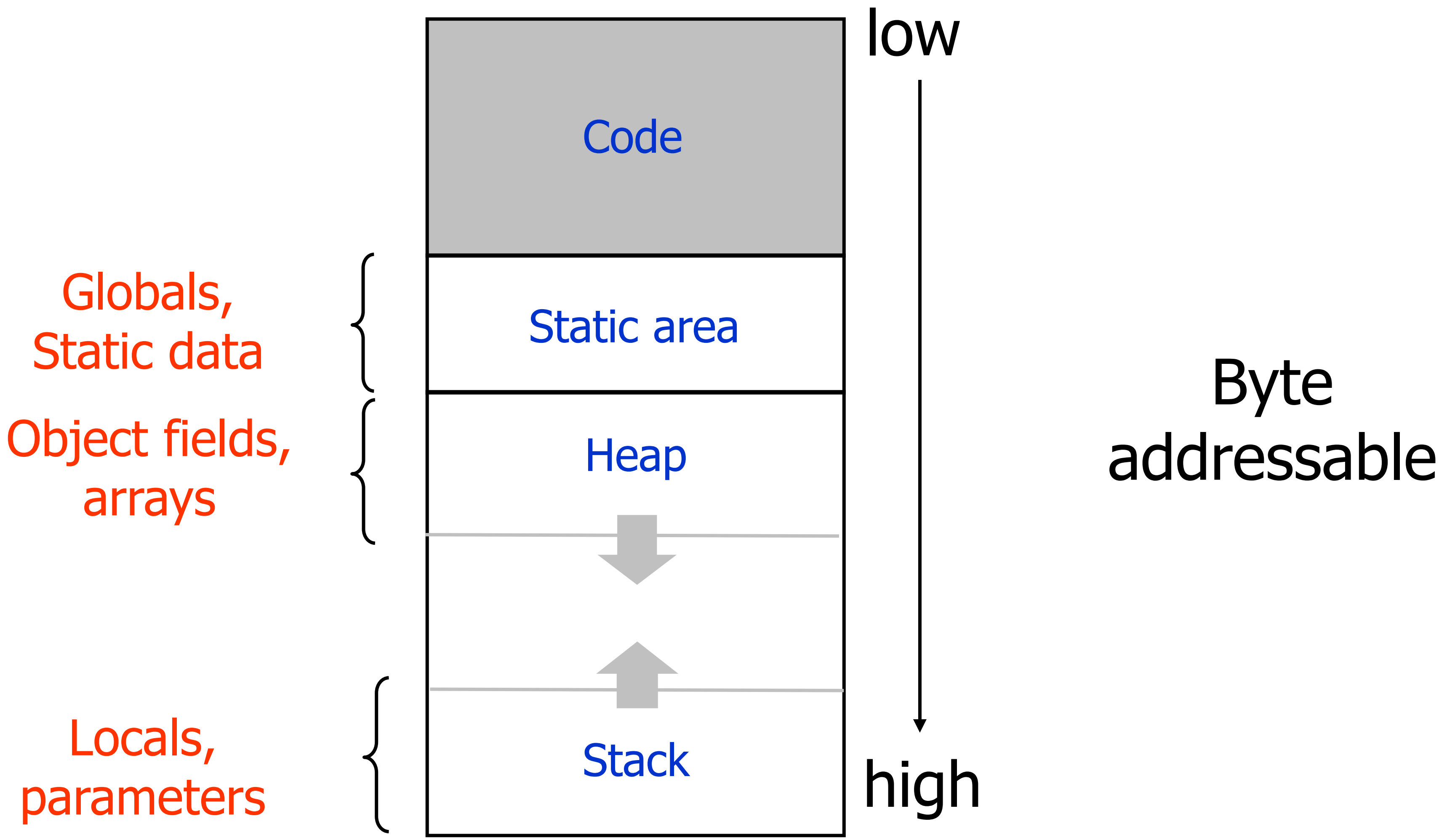
Note on register names

Registers are general-purpose: can be used for anything programmer wants

Historically, the registers were intended to be used as shown below, hence their odd names:

- AX/EAX/RAX: accumulator
- BX/EBX/RBX: base
- CX/ECX/RCX: counter
- DX/EDX/RDX: data/general
- SI/ESI/RSI: "source index" for string operations.
- DI/EDI/RDI: "destination index" for string operations.
- SP/ESP/RSP: stack pointer for top address of the stack.
- BP/EBP/RBP: stack base pointer for holding the address of the current stack frame.
- IP/EIP/RIP: instruction pointer. Holds the current instruction address.

Memory Layout



x86 Quick Overview

- Instructions:
  - Arithmetic: add, sub, inc, mod, idiv, imul, etc.
  - Logic: and, or, not, xor
  - Comparison: cmp, test
  - Control flow: jmp, jcc, jecz
  - Function calls: call, ret
  - Data movement: mov (many variants)
  - Stack manipulations: push, pop
  - Other: lea

Instruction set

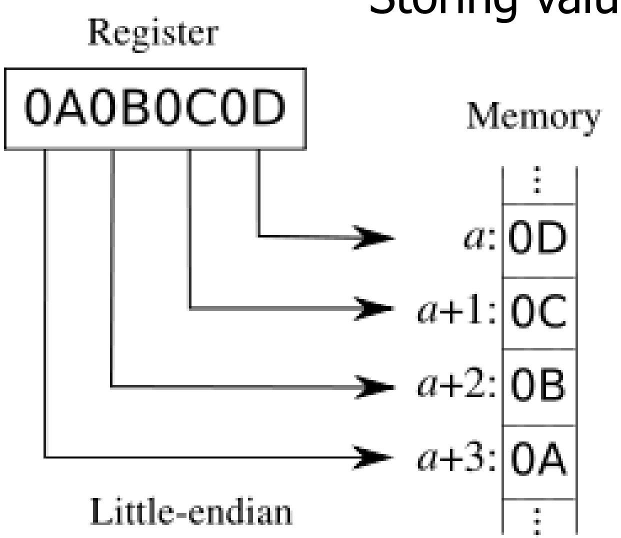
- x86 instruction set: two-address instruction set
  - Op a, b
    - a,b specify the two operands
    - result of operation is stored in b
      - warning: AT&T and Intel formats are different: see last slide
      - we will assume AT&T format in slides
    - a,b: registers or memory address
    - at most one operand can be in memory
    - memory addresses can be specified as offset from ebp (or other registers)
      - pushl 8(%ebp)
      - more generally, address can be specified as disp(base,offset,scale)
  - Examples:
    - addl $3, %eax //add constant 3 to register eax
    - movl %eax, %ebx //move contents of register eax to register ebx
    - movl 8(%ebp), %eax //move contents at memory address (8 + contents(ebp)) //to register eax
    - movl %eax, 8(%ebx,%ecx,4) //effective address is 8 + contents(%ebx) + 4*contents(%ecx)

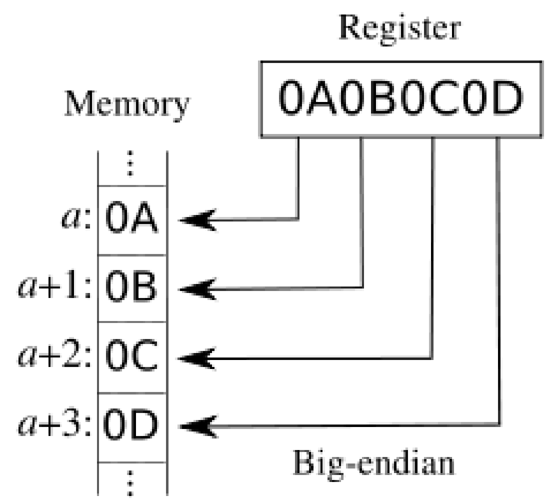
Little-endian

x86 instruction set can address bytes and supports data of different sizes, so you have to be aware of the representation of data.

How are 32-bit quantities stored in memory?

Storing value 0x0A0B0C0D in memory



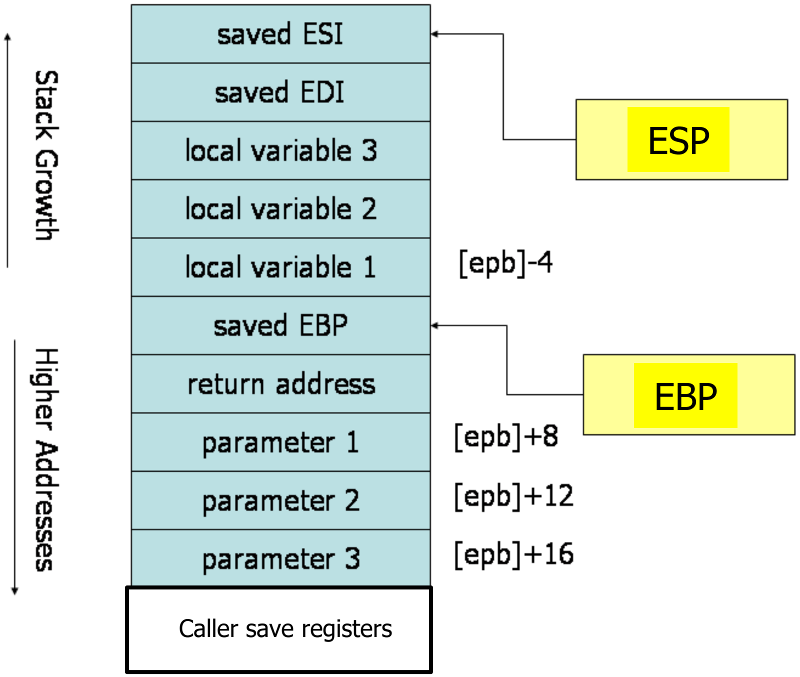


x86 is “little-endian”

Condition code register

- Condition code register
  - Bits in this register are set implicitly when instructions are executed
  - (eg) ZF bit is the zero flag and is set if the result of the operation is zero
  - (eg) SF bit is the sign flag and is set if the result of the operation is negative
  - ....
- Branch instructions can test one or more flags and branch conditionally on the outcome
  - (eg) je/jz is “jump if equal”: jumps if ZF is set
  - (eg) jne/jnz is “jump if not equal”
  - Many other conditional branch operations

gcc/icc stack frame



- arguments are pushed right to left

  f(arg1,arg2,…,argN)

- registers are saved by caller and callee

  gcc convention
  - caller save: eax,ecx,edx
  - callee save: ebp,ebx,esi,edi

- ebp (FBR) is one of callee save registers

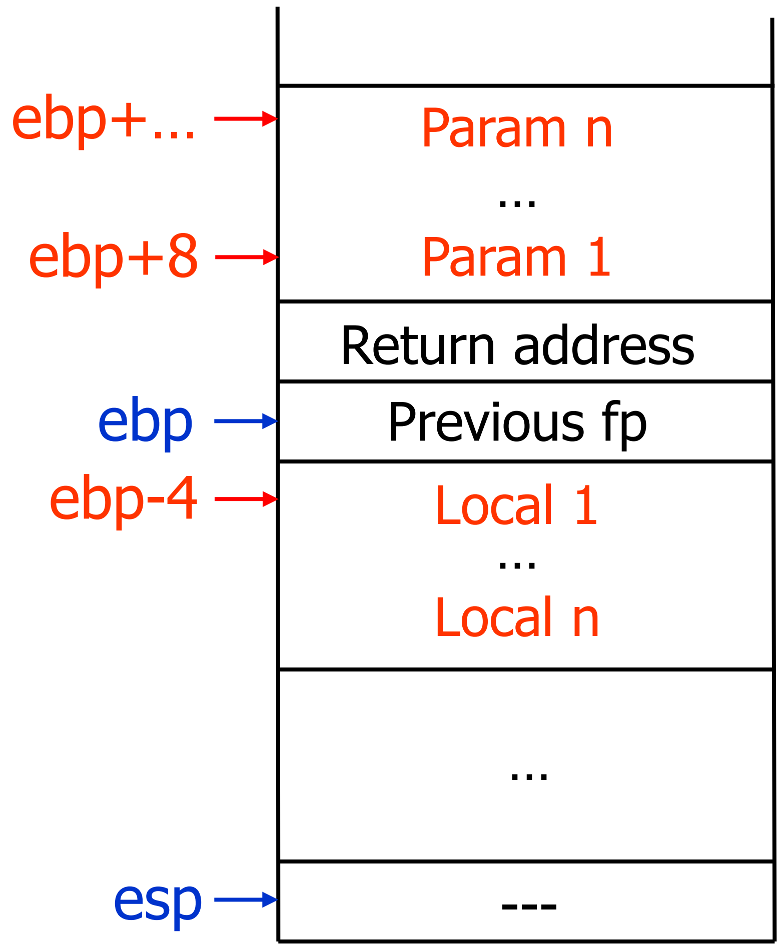
- eax is used to return a value from function

- on x64, registers are used to pass arguments

Accessing Stack Variables

- To access stack variables: use offsets from ebp

- Example:
  8(%ebp) = parameter 1
  12(%ebp) = parameter 2
  -4(%ebp) =local 1



Accessing Stack Variables

- Translate accesses to variables:
  - For parameters, compute offset from %ebp using:
    - Parameter number
    - Sizes of other parameters
  - For local variables, look at data layout and assign offsets from frame pointer to each local
- Example:
  - a: local, offset-4
  - p: parameter, offset+16, q: parameter, offset+8
  - Assignment a = p + q becomes equivalent to:

    -4(%ebp) = 16(%ebp) + 8(%ebp)
  - How to write this in assembly?

Arithmetic

- How to translate: p+q ?
  - Assume p and q are locals or parameters
  - Determine offsets for p and q
  - Perform the arithmetic operation
- Problem: the ADD instruction in x86 cannot take both operands from memory; notation for possible operands:
  - mem32: register or memory 32 bit (similar for r/m8, r/m16)
  - reg32: register 32 bit (similar for reg8, reg16)
  - imm32: immediate 32 bit (similar for imm8, imm16)
  - At most one operand can be mem !
- Translation requires using an extra register
  - Place p into a register (e.g. %ecx): mov 16(%ebp), %ecx
  - Perform addition of q and %ecx: add 8(%ebp), %ecx

Data Movement

- Translate a = p+q:
  - Load memory location (p) into register (%ecx) using a move instr.
  - Perform the addition
  - Store result from register into memory location (a):

```
mov 16(%ebp), %ecx        (load)
add 8(%ebp), %ecx   (arithmetic)
mov %ecx, -8(%ebp)        (store)
```

- Move instructions cannot have two memory operands

  Therefore, copy instructions must be translated using an extra register:

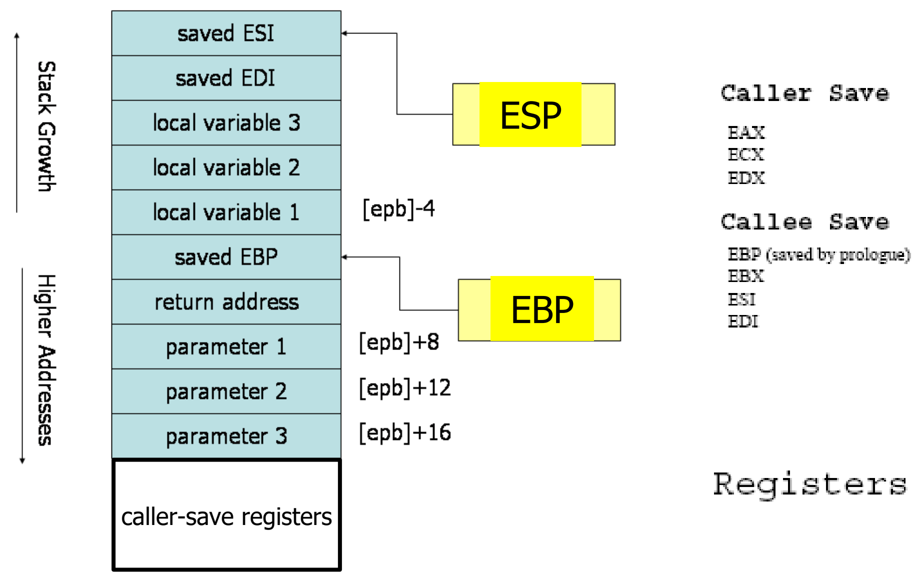
  a = p ⇒
```
mov 16(%ebp), %ecx
mov %ecx, -8(%ebp)
```

- However, loading constants doesn't require extra registers:

  a = 12 ⇒
```
mov $12, -8(%ebp)
```

Exercise: write assembly for example

```
int plus3 (int x) { int res = x + 3; return res; }
int doit (int x) { return plus3 (x); }
int main (void) {  return doit (8); }
_plus3:
        pushl    %ebp            // save ebp
        movl     %esp, %ebp      //ebp points to current frame
        pushl    %esi            //save register esi
        movl     8(%ebp), %esi   //x → esi
        addl     $3, %esi        //esi + 3 → esi
        movl     %esi, %eax      //eax now has return value
        popl     %esi            //restore esi
        movl     %ebp, %esp      //pop local variables
        popl     %ebp            //restore ebp
        ret
_doit:
        pushl    %ebp
        movl     %esp, %ebp
        pushl    8(%ebp)
        call     _plus3
        movl     %ebp, %esp
        popl     %ebp
        ret
_main:
        pushl    %ebp
        movl     %esp, %ebp
        pushl    $8
        call     _doit
        movl     %ebp, %esp
        popl     %ebp
        ret
```



Accessing Global Variables

- Global (static) variables and constants not stack allocated
- Have fixed addresses throughout the execution of the program
  - Compile-time known addresses (relative to the base address where program is loaded)
  - Hence, can directly refer to these addresses using symbolic names in the generated assembly code

- Example: string constants

```
str:  .string   “Hello world!“
```

  - The string will be allocated in the static area of the program
  - Here, “str” is a label representing the address of the string
  - Can use $str as a constant in other instructions:

```
push $str
```

Control-Flow

- Label instructions
  - Simply translated as labels in the assembly code
  - E.g., label2: mov $2, %ebx

- Unconditional jumps:
  - Use jump instruction, with a label argument
  - E.g., jmp label2

- Conditional jumps:
  - Translate conditional jumps using test/cmp instructions:
  - E.g., tjump b L ➔

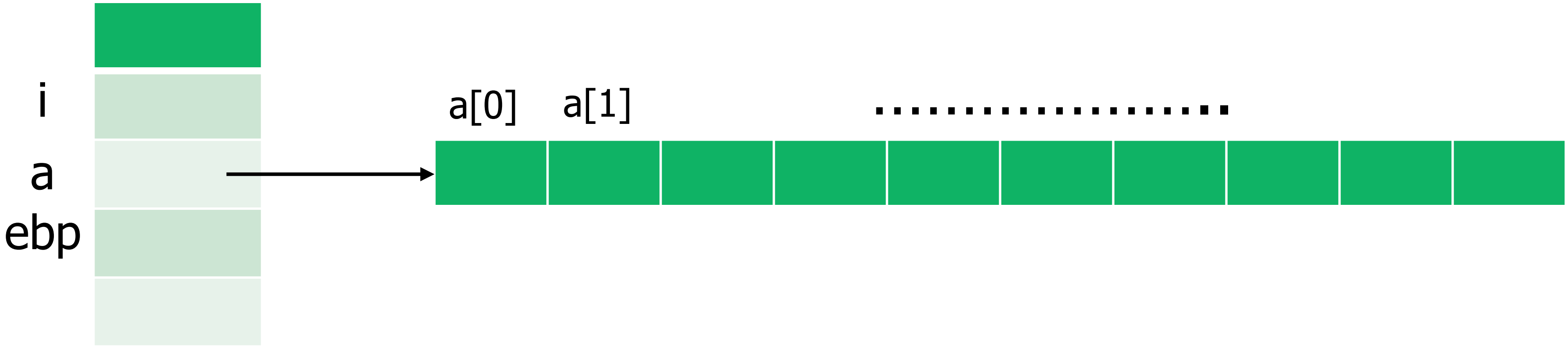
    ```
    cmp %ecx, $0
    jnz L
    ```

    where %ecx hold the value of b, and we assume booleans are represented as 0=false, 1=true

Data structures: 1-D arrays

- Array accesses in language with dynamic array size
  - access a[i] requires:
    - Compute address of element: a + i * size
    - Access memory at that address
  - Can use indexed memory accesses to compute addresses
  - Example: assume size of array elements is 4 bytes, and local variables a, i (offsets –4, -8)

a[i] = 1	mov –4(%ebp), %ebx	(load a)
	mov –8(%ebp), %ecx	(load i)
	mov $1, (%ebx,%ecx,4)	(store into the heap)

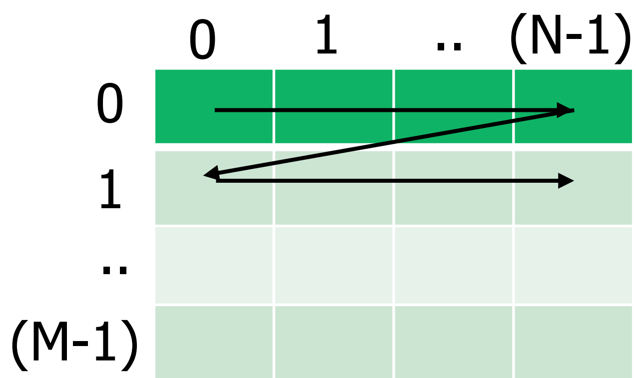


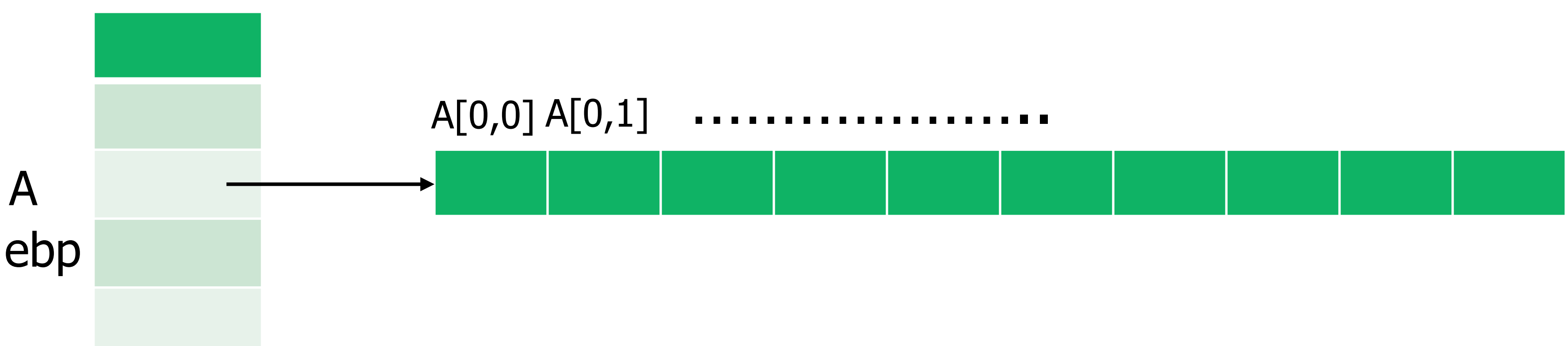
Data structures: multi-dimensional arrays (I)

- Multi-dimensional arrays
  - Elements of array are stored sequentially in memory in some order
- Two important orders
  - Row-major order: elements of each row are contiguous in memory and rows are stored one after another starting from the first row (all languages other than FORTRAN)
  - Column-major order: similar to row-major but columns are stored contiguously, not rows (FORTRAN)
- Array allocated on heap (using malloc or new)
  - Pointer to array (address of A[0,0]) is stored on stack

Data structures: multi-dimensional arrays (II)

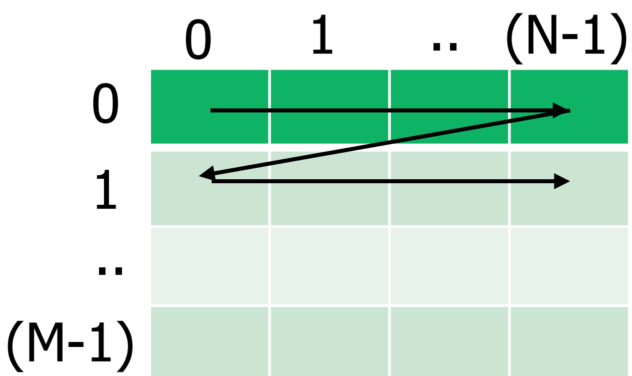
- Address arithmetic:
  - Assume array A: MxN of ints/floats/whatever (assume each element requires “size” bytes)
  - Array allocated on heap in row major order
  - Starting address of A is stored at -4(%ebp) for example
  - What is address of A[i,j]?
- Address(A[r,c]) = -4(%ebp) + (r*N+c)*size

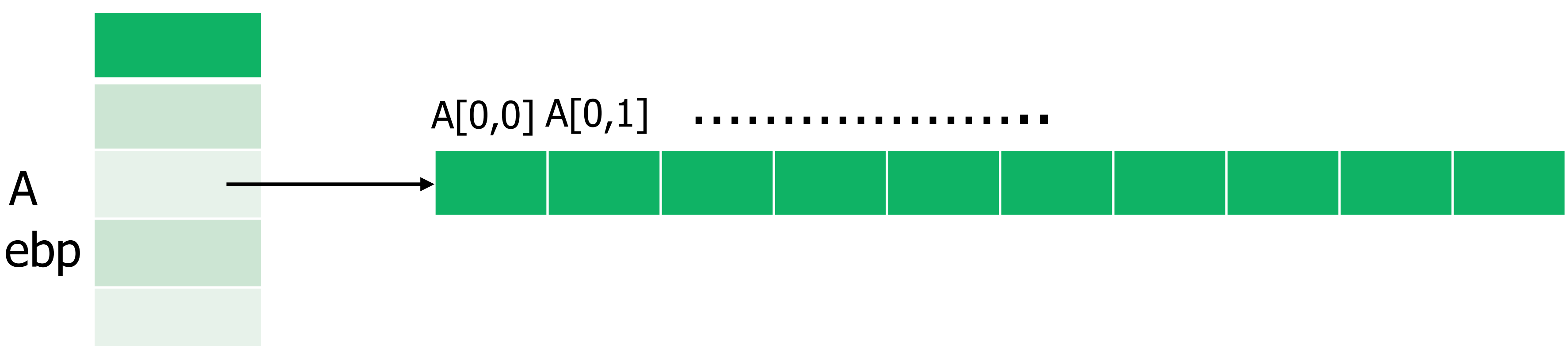




Data structures: multi-dimensional arrays (III)

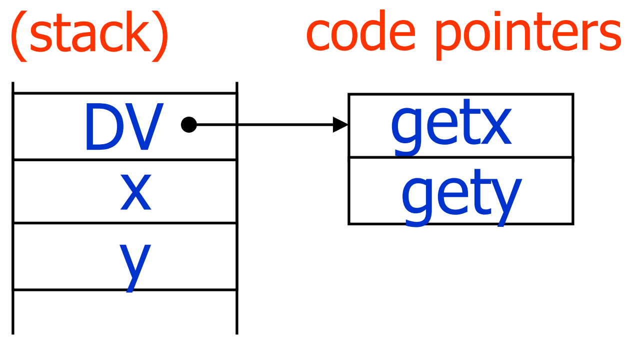
- Usually array elements are accessed within loops
- Optimizing compilers will optimize the address arithmetic for array access using loop invariant removal and strength reduction (see later)
- Sequential accesses to row elements
  - Register points into array
  - Incremented by "size" after each access to get to the next element





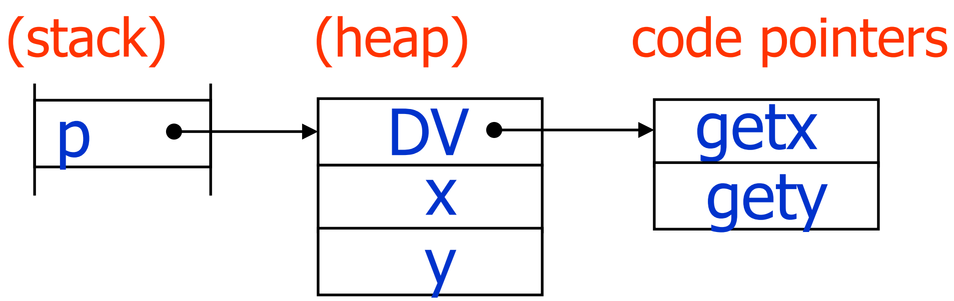
Data structures: objects

- Objects can be stack- or heap-allocated
- Example: Point type
  - Fields: x,y
  - Methods: getx, gety



- Stack allocation:

  (C++) Point p;



- Heap:

  (C++)

  Point *p = new Point;

  (Java)

  Point p = new Point();

Run-time Checks

- Run-time checks:
  - Check if array/object references are non-null
  - Check if array index is within bounds
- Example: array bounds checks:
  - if v holds the address of an array, insert array bounds checking code for v before each load (...=v[i]) or store (v[i] = ...)
  - Assume array length is stored just before array elements:

```
cmp $0, -12(%ebp)          (compare i to 0)
jl ArrayBoundsError        (test lower bound)
mov –8(%ebp), %ecx         (load v into %ecx)
mov –4(%ecx), %ecx         (load array length into %ecx)
cmp –12(%ebp), %ecx        (compare i to array length)
jle ArrayBoundsError       (test upper bound)
. . .
```

X86 Assembly Syntax

- Two different notations for assembly syntax:
  - AT&T syntax and Intel syntax
  - In the examples: AT&T (gcc) syntax

- Summary of differences:

	AT&T	Intel
Order of operands	op a, b : b is destination	op a, b : a is destination
Memory addressing	disp(base,offset,scale)	[base + offset*scale + disp]
Size of memory operands	instruction suffixes (b,w,l) (e.g., movb, movw, movl)	operand prefixes (byte ptr, word ptr, dword ptr)
Registers	%eax, %ebx, etc.	eax, ebx, etc.
Constants	$4, $foo, etc	4, foo, etc

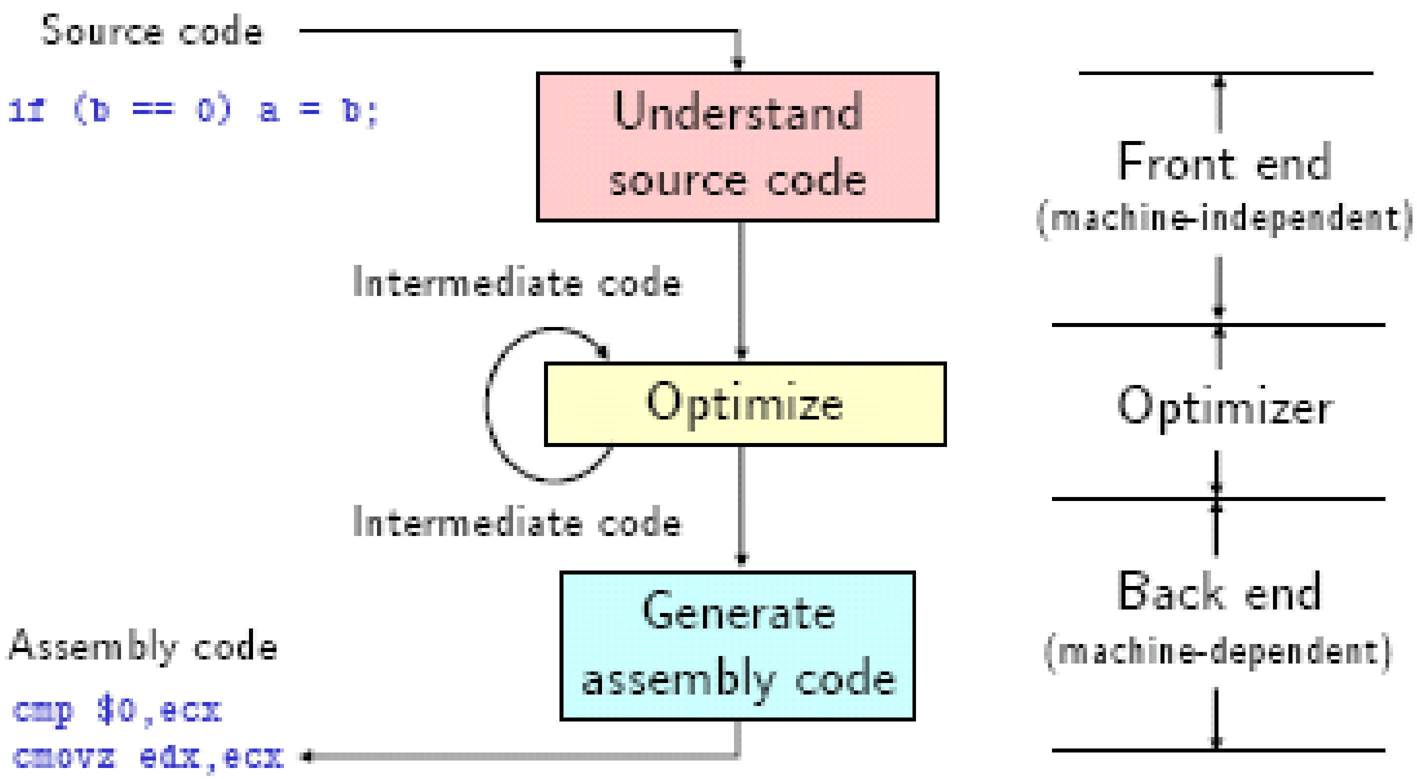
Tutorial

- This website has a simple example with comments

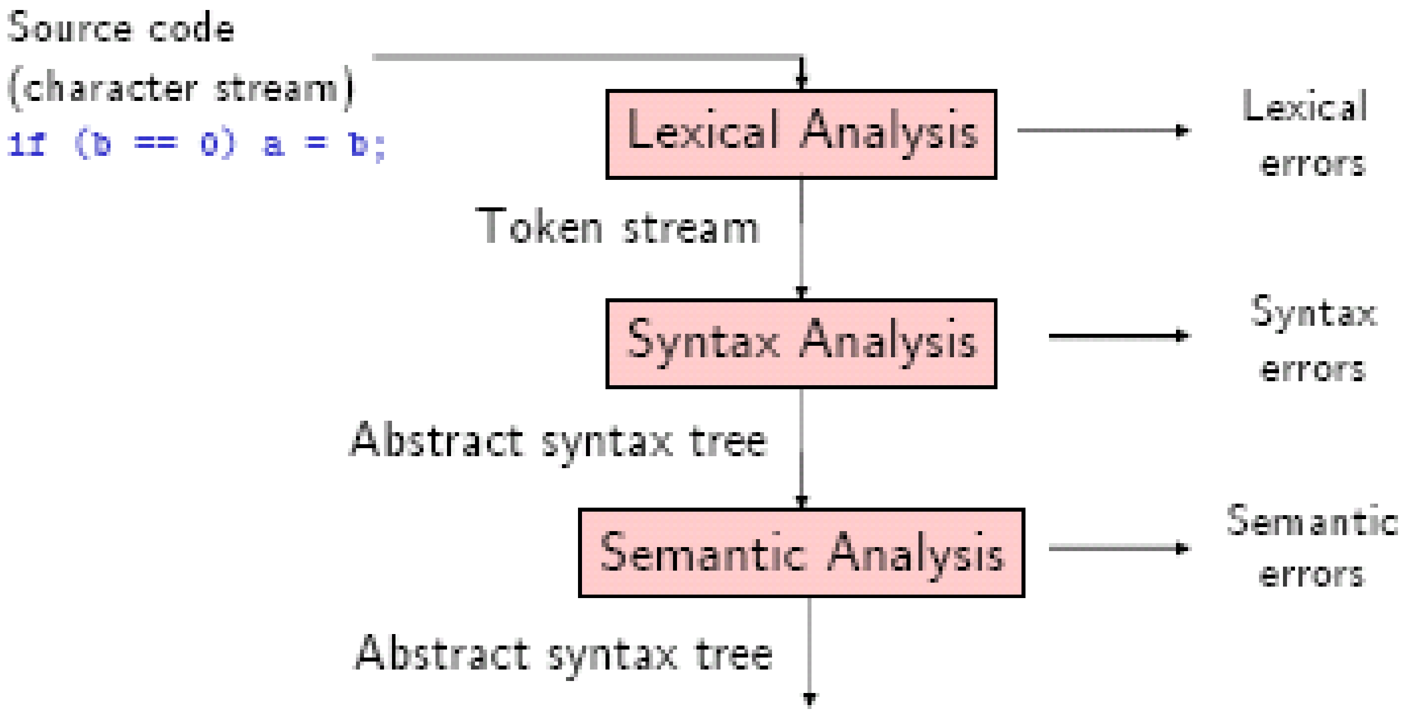
https://eli.thegreenplace.net/2011/02/04/where-the-top-of-the-stack-is-on-x86/

Introduction to Compilers

Optimizing compiler structure



Front-end structure

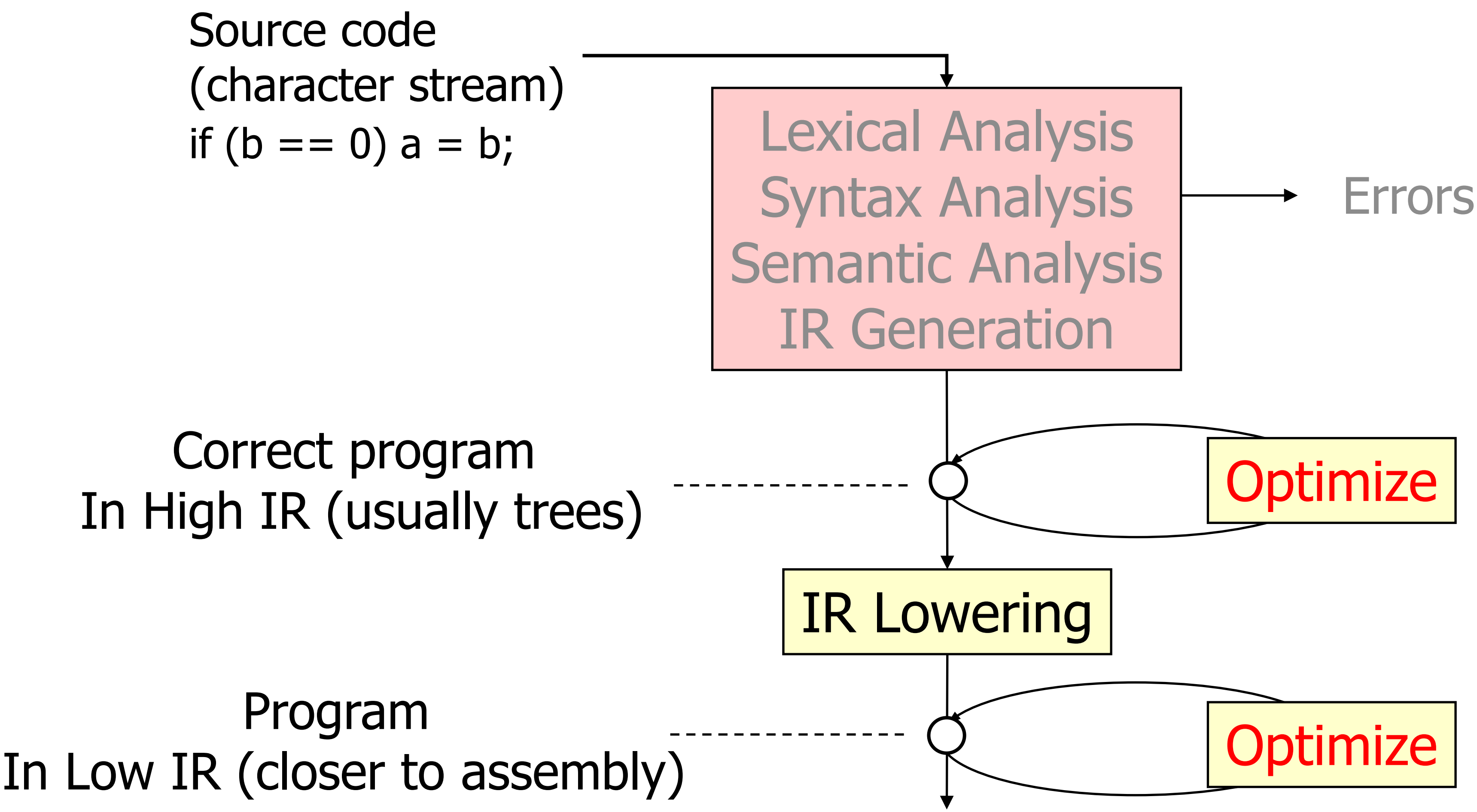


Syntax analysis is also known as parsing.

What Next?

- At this point we could generate assembly code
- Better:
  - Optimize the program first
  - Then generate code
- If optimization performed at the IR level, then they apply to all target machines

Optimizations



When to Apply Optimizations

High IR	Function inlining Function cloning
Low IR	Constant folding Constant propagation Value numbering Dead code elimination Loop-invariant code motion Common sub-expression elimination Strength reduction Constant folding & propagation Branch prediction/optimization Loop unrolling
Assembly	Register allocation Cache optimization

What are Optimizations?

- Optimizations = code transformations that *improve* the program

- Different kinds
  - space optimizations: improve (reduce) memory use
  - time optimizations: improve (reduce) execution time

- Code transformations must be safe!
  - They must preserve the meaning of the program

Why Optimize?

- Programmers don't always write optimal code – can recognize ways to improve code (e.g., avoid recomputing same expression)

- High-level language may make some optimizations inconvenient or impossible to express

```
a[ i ][ j ] = a[ i ][ j ] + 1;
```

- High-level unoptimized code may be more readable: cleaner, modular

```
int square(x) { return x*x; }
```

Where to Optimize?

- Usual goal: improve time performance
- Problem: many optimizations trade off space versus time
- Example: loop unrolling
  - Increases code space, speeds up one loop
  - Frequently executed code with long loops: space/time tradeoff is generally a win
  - Infrequently executed code: may want to optimize code space at expense of time
- Want to optimize program hot spots

Many Possible Optimizations

- Many ways to optimize a program
- Some of the most common optimizations:

  Function Inlining
  Function Cloning
  Constant folding
  Constant propagation
  Dead code elimination
  Loop-invariant code motion
  Common sub-expression elimination
  Strength reduction
  Branch prediction/optimization
  Loop unrolling

Constant Propagation

- If value of variable is known to be a constant, replace use of variable with constant
- Example:

```
n = 10
c = 2
for (i=0; i<n; i++) { s = s + i*c; }
```

- Replace n, c:

```
for (i=0; i<10; i++) { s = s + i*2; }
```

- Each variable must be replaced only when it has known constant value:
  - Forward from a constant assignment
  - Until next assignment of the variable

Constant Folding

- Evaluate an expression if operands are known at compile time (i.e., they are constants)
- Example:

  x = 1.1 * 2; ⇒ x = 2.2;

- Performed at every stage of compilation
  - Constants created by translations or optimizations

  int x = a[2] ⇒ t1 = 2*4

  t2 = a + t1

  x = *t2

Algebraic Simplification

- More general form of constant folding: take advantage of usual simplification rules

a * 1 ⇒ a	a * 0 ⇒ 0
a / 1 ⇒ a	a + 0 ⇒ a
b || false ⇒ b	b && true ⇒ b

- Repeatedly apply the above rules

  (y*1+0)/1 ⇒ y*1+0 ⇒ y*1 ⇒ y

- Must be careful with floating point!

Copy Propagation

- After assignment x = y, replace uses of x with y
- Replace until x is assigned again

`x = y;`
`if (x > 1)`
`  s = x * f(x - 1);`
	$\Rightarrow$	`x = y;`
		`if (y > 1)`
		`  s = y * f(y - 1);`

- What if there was an assignment y = z before?
  - Transitively apply replacements

Common Subexpression Elimination

- If program computes same expression multiple time, can reuse the computed value
- Example:

a = b+c;
c = b+c;
d = b+c;
	⇒	a = b+c;
		c = a;
		d = b+c;

- Common subexpressions also occur in low-level code in address calculations for array accesses:

```
a[i] = b[i] + 1;
```

Unreachable Code Elimination

- Eliminate code that is never executed
- Example:

```
#define debug false
s = 1;                          ⇒      s = 1;
if (debug)
    print("state = ", s);
```

- Unreachable code may not be obvious in low IR (or in high-level languages with unstructured "goto" statements)

Unreachable Code Elimination

- Unreachable code in while/if statements when:
  - Loop condition is always false (loop never executed)
  - Condition of an if statement is always true or always false (only one branch executed)

```
if (false) S                ⇒  ;

if (true) S else S'         ⇒  S
if (false) S else S'        ⇒  S'

while (false) S       ⇒  ;
while (2>3) S         ⇒  ;
```

Dead Code Elimination

- If effect of a statement is never observed, eliminate the statement

```
x = y+1;
y = 1;                ⇒      y = 1;
x = 2*z;                     x = 2*z;
```

- Variable is *dead* if value is never used after definition
- Eliminate assignments to dead variables
- Other optimizations may create dead code

Loop Optimizations

- Program hot spots are usually loops (exceptions: OS kernels, compilers)
- Most execution time in most programs is spent in loops: 90/10 is typical
- Loop optimizations are important, effective, and numerous

Loop-Invariant Code Motion

- If result of a statement or expression does not change during loop, and it has no externally-visible side-effect (!), can hoist its computation out of the loop
- Often useful for array element addressing computations – invariant code not visible at source level
- Requires analysis to identify loop-invariant expressions

Code Motion Example

- Identify invariant expression:

```
for(i=0; i<n; i++)
    a[i] = a[i] + (x*x)/(y*y);
```

- Hoist the expression out of the loop:

```
c = (x*x)/(y*y);
for(i=0; i<n; i++)
    a[i] = a[i] + c;
```

Another Example

- Can also hoist statements out of loops
- Assume x not updated in the loop body:

```
...
while (...) {
      y = x*x;
      ...
}
...
```

⇒

```
...
y = x*x;
while (...) {
      ...
}
...
```

- ... Is it safe?

Strength Reduction

- Replaces expensive operations (multiplies, divides) by cheap ones (adds, subtracts)
- Strength reduction more effective in loops and useful for address arithmetic
- Induction variable = loop variable whose value is depends linearly on the iteration number
- Apply strength reduction to induction variables

```
s = 0;
for (i = 0; i < n; i++) {
        v = 4*i;
        s = s + v;
}
```

⇒

```
s = 0; v = -4;
for (i = 0; i < n; i++) {
        v = v+4;
        s = s + v;
}
```

Strength Reduction

- Can apply strength reduction to computation other than induction variables:

$$x * 2 \Rightarrow x + x$$

$$i * 2^c \Rightarrow i << c$$

$$i / 2^c \Rightarrow i >> c$$

Induction Variable Elimination

- If there are multiple induction variables in a loop, can eliminate the ones that are used only in the test condition
- Need to rewrite test using the other induction variables
- Usually applied after strength reduction

```
s = 0; v=-4;
for (i = 0; i < n; i++) {
        v = v+4;
        s = s + v;
}
```

$\Rightarrow$

```
s = 0; v = -4;
for (; v < (4*n-4);) {
        v = v+4;
        s = s + v;
}
```

Loop Unrolling

- Execute loop body multiple times at each iteration
- Example:

```
for (i = 0; i< n; i++) { S }
```

- Unroll loop four times:

```
for (i = 0; i < n-3; i+=4) { S; S; S; S; }
for (      ; i < n; i++) S;
```

- Gets rid of ¾ of conditional branches!
- Space-time tradeoff: program size increases

Function Inlining

- Replace a function call with the body of the function:

```
int g(int x)  { return f(x)-1; }
int f(int n)  { int b=1; while (n--) { b = 2*b }; return b; }

int g(int x)  { int r;
                int n = x;
                { int b =1; while (n--) { b = 2*b }; r = b }
                return r – 1; }
```

- Can inline methods, but more difficult
- ... how about recursive procedures?

Function Cloning

- Create specialized versions of functions that are called from different call sites with different arguments

```
void f(int x[], int n, int m) {
        for(int i=0; i<n; i++) { x[i] = x[i] + i*m; }
}
```

- For a call f(a, 10, 1), create a specialized version of f:

```
void f1(int x[]) {
        for(int i=0; i<10; i++) { x[i] = x[i] + i; }
}
```

- For another call f(b, p, 0), create another version f2(…)

When to Apply Optimizations

High IR	Function inlining Function cloning
Low IR	Constant folding Constant propagation Value numbering Dead code elimination Loop-invariant code motion Common sub-expression elimination Strength reduction Constant folding & propagation Branch prediction/optimization Loop unrolling
Assembly	Register allocation Cache optimization

Summary

- Many useful optimizations that can transform code to make it faster
- Whole is greater than sum of parts: optimizations should be applied together, sometimes more than once, at different levels