Domain-Specific Analysis

Last time

- Context-sensitive pointer analysis

Today

- A break from pointer analysis
- Exploiting domain-specific information in analysis and optimization

Motivation

Two different views of software

Compiler's view

- Abstractions: numbers, pointers, loops
- Operators: `+, -, *, ->, []`

Programmer's view

- Abstractions: files, matrices, locks, graphics
- Operators: read, factor, lock, draw

- In high-level languages even language constructs can have this problem.

This discrepancy causes a problem...

Find the Error – Part 1

Example:

```
switch (var_83) {
case 0: func_24();
  break;
case 1: func_29();
  break;
}
case 2: func_78();
```

Error: `case` outside of `switch` statement

- Part of the language definition
- Error reported at compile time
- Compiler indicates the location and nature of error

Find the Error – Part 2

Example:

```
struct __sue_23 * var_72;
char var_81[100];
var_72 = libfunc_84(__str_14, __str_65);
libfunc_44(var_72);
libfunc_38(var_81, 100, 1, var_72);
```

Improper call to `libfunc_38`

- Syntax is correct – no compiler message
- Fails at run-time

Problem: what does `libfunc_38` do?

This is how compilers view reusables

Find the Error – Part 3

Example:

```
FILE * my_file;
char buffer[100];
my_file = fopen(“my_data”, “r”);
fclose(my_file);
fread(buffer, 100, 1, my_file);
```

Improper call to `fread()` after `fclose()`

- The *names* reveal the mistake

No traditional compiler reports this error

- Run-time system: how does the code fail?
- Code review: rarely this easy to spot

Missed Opportunities

Libraries encapsulate domain-specific semantics

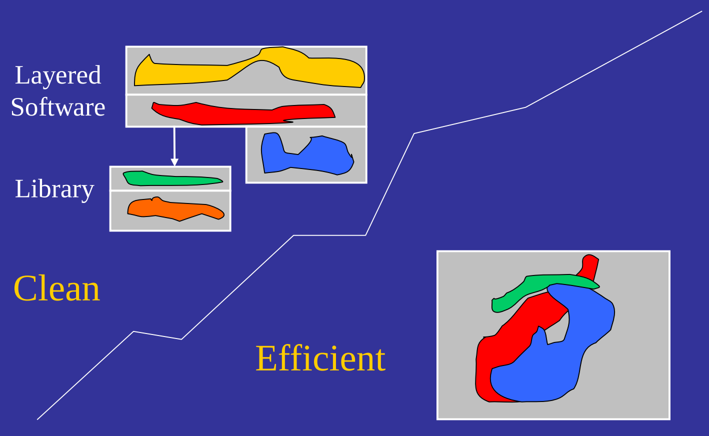
- This semantic information provides many opportunities for error checking
- This semantic information provides many opportunities for optimization
- This information is unavailable to conventional compilers

Libraries are domain-specific languages

- Second-class languages

The implications are significant . . .

The Choice: Abstraction vs. Efficiency



Outline

The Problem

Domain-specific optimization

– PLAPACK library example

Domain-specific program checking

– Format String Vulnerability example

Results

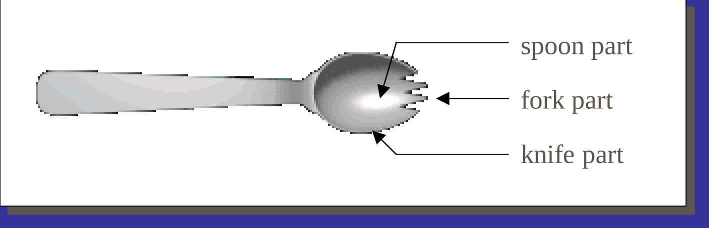
The Challenge

Software libraries offer many benefits

The challenge facing libraries

- Different clients have different needs
- No single implementation is ideal for all situations

Real World Analogy: The Spork (really a Spofe or something like that)



Interface Bloat

Common approach

- Create lots of specialized routines
- Let user choose the appropriate routine

Interface Bloat in MPI

Short term problems:

- Complex interface
- Specialized routines can be difficult to use

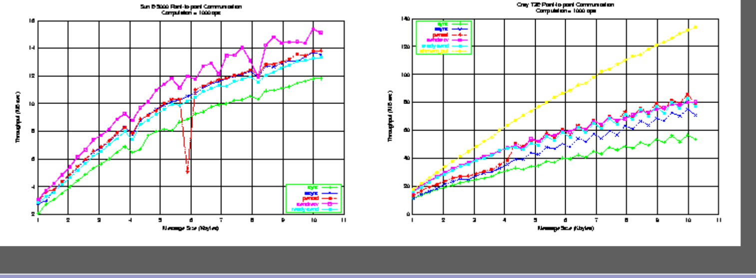
12 ways (modes) to perform point-to-point communication:

	Normal	Sync	Ready	Buffered
Normal	MPI_Send	MPI_Ssend	MPI_Rsend	MPI_Bsend
Nonblock	MPI_Isend	MPI_Issend	MPI_Irsend	MPI_Ibsend
Persistent	MPI_Send_init	MPI_Ssend_init	MPI_Rsend_init	MPI_Bsend_init

Interface Bloat in MPI

Long term problems:

- No performance portability
- Application becomes less general



Problems with Interface Bloat

Premature optimization

– Requires manual changes to application source
– Embeds optimizations into application source

Long Term Problems

– Complicates maintenance
– Defeats portability

How Can We Avoid Interface Bloat?

Libraries are domain-specific languages

– No new syntax
– No compiler support

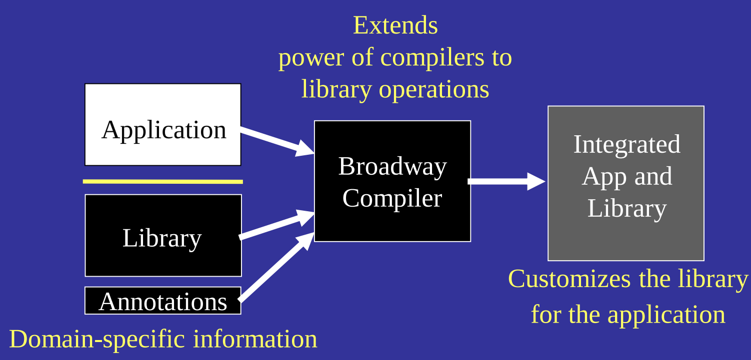
```
c = a * b;          /* language primitive */

bnMultiply(&c,a,b)/* library call*/
```

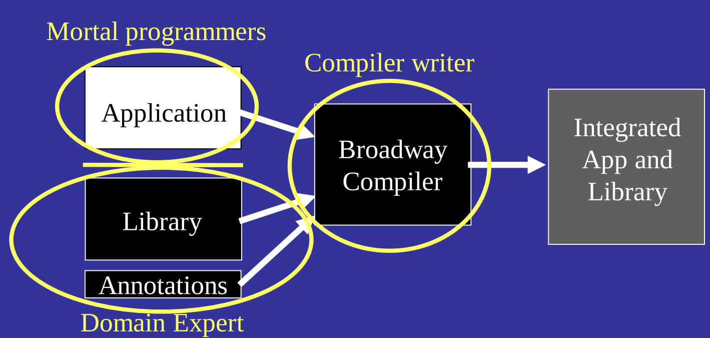
Libraries encapsulate domain-specific semantics

– This semantic information provides many opportunities for analysis and optimization
– Make this information available to compilers

Our Solution: The Broadway Compiler [Guyer and Lin'99]

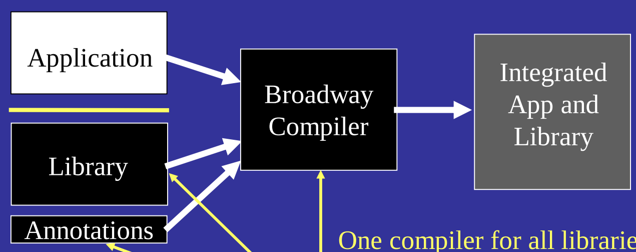


Separation of Concerns



Separation of Concerns

The applications programmer does not see the annotations



One compiler for all libraries

One set of annotations per library

Hard parts are reused many times

Hard parts are hidden from the mortals

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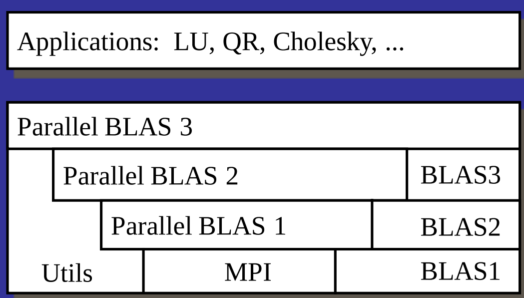
Introduction to PLAPACK

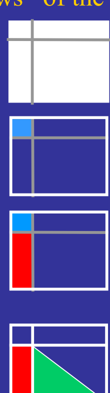
PLAPACK

- Parallel Linear Algebra Package
- Developed by van de Geijn, *et al.* [van de Geijn'97]
- Developed for high performance
- ≈ 40,000 lines of C code



Typical PLAPACK Application

"views" of the data

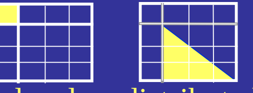


```
while (True) {
  PLA_Obj_global_length(ABR, &length);
  if (length == 0) break;

  PLA_Obj_split_4(ABR, nb, nb, &A11, &A12,
                                &A21, &A22);

  Cholesky(A11);

  PLA_Trsm(PLA_SIDE_RIGHT, PLA_LOW_TRIAN,
           PLA_TRANS, PLA_NONUNIT_DIAG,
           one, A11, A21);

  PLA_Syrk(PLA_LOW_TRANS, PLA_NO_TRANS,
           minus_one, A21, one, ABR);
}
```

Views in PLAPACK

The notion of **views** can be used to perform optimizations

Views can have special properties

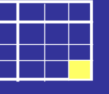


local distributed

These properties can be reasoned about by programmers

These properties can be exploited by using special algorithms

```
PLA_Trsm       (PLA_SIDE_RIGHT, PLA_LOW_TRIAN,
                PLA_TRANS, PLA_NONUNIT_DIAG,
                one, A11, A21);
PLA_Trsm_local (PLA_SIDE_RIGHT, PLA_LOW_TRIAN,
                PLA_TRANS, PLA_NONUNIT_DIAG,
                one, A11, A21);
```



These properties cannot be inferred by conventional compilers

View-Based Optimizations

Given the original program

- Compiler analyzes the flow of **view** information through the program
- Compiler determines when specialized routines can be used

```
PLA_Obj_view_all(A, &ABR)
while (True) {
  PLA_Obj_length(ABR, &b);
  b = min(b, nb);
  if (b==0) break;
  PLA_Obj_split_4(ABR,b,b,&A11..
                      &A21, &ABR);
  Cholesky(A11);
  PLA_Trsm(PLA_SIDE_RIGHT, …)
  PLA_Syrk(PLA_LOW_TRIAN, …)
}
```

PLA_Trsm() and PLA_Syrk() are overly general– they work for any distribution

Specialization Has Many Benefits

If a View is empty

```
PLA_Obj_view_all(A, &A11)
do {
  PLA_Trsm(A11);
  PLA_Obj_len(A11, &len);
  len = min(length, nb);
  PLA_Obj_split_4(A11,len,...);
} while (len>0)
```

This becomes a no-op

This becomes dead code

This loop disappears

The interaction of optimizations produces many benefits

What Information is Needed?

Define special properties

– Views can be distributed or local

Specify how library routines affect these properties

– Which routines create views, shrink views, etc.?

Specify when specialized routines can be used

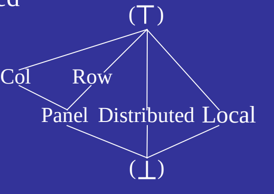
– How can view information be used to invoke specialized routines?

Library-specific Analysis

Annotations specify analysis problems

- Define a simple **flow value** – like an enumeration
  - The lattice structure and meet function are implied

```
property Distribution : { Distributed,
                          Local,
                          Panel { Row, Col }}
```



- Define **transfer functions** for library routines

```
procedure Copy_matrix(src, dest)
{
  analyze Distribution {
    if (src is-exactly Local) { dest <- Local }
  }
}
```


Specifying Optimizations

Annotations define specializations

- Replace a library call based on analysis results

```
procedure ParallelMatrixMultiply(A)
{
  when (Distribution : A is-exactly Local)
    replace-with %{ SeqMatrixMultiply($A); }%
}
```

Traditional optimizations extended to libraries

- Constant propagation
- Dead-code elimination

Dependence Annotations

Basic annotations **convey data dependence information**

– Defs and uses of procedure parameters

```
modify {};
access {view};
```

– Pointer relationships

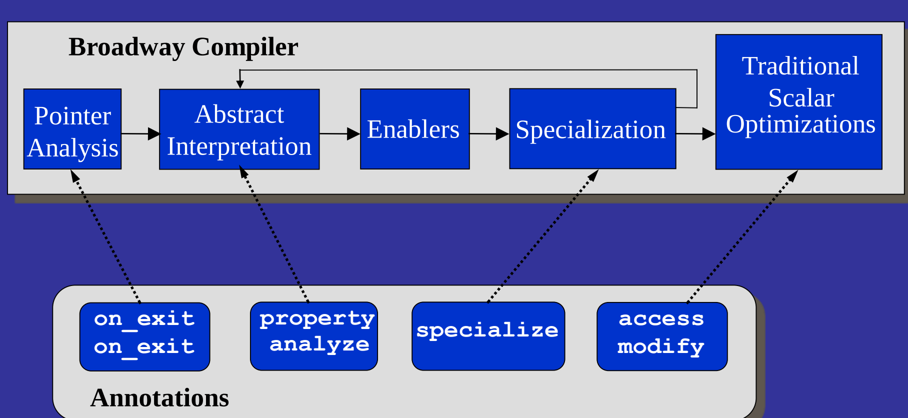
```
on_entry {obj-->view};
on_exit  {A11-->view11, A12-->view12,
          A21-->view21, A22-->view22};
```

– These annotations are important for describing complex data structures

How Do We Use This Information?

The Broadway Compiler has configurable phases

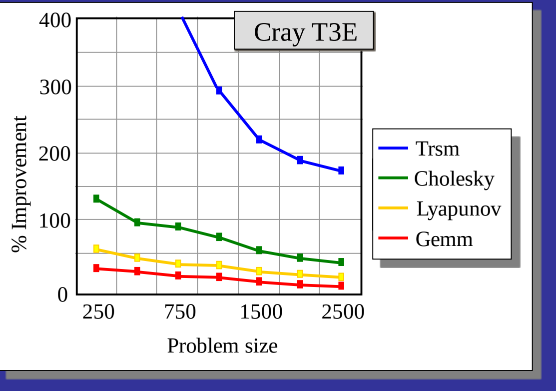
– Each phase draws information from the appropriate annotation



Does It Work?

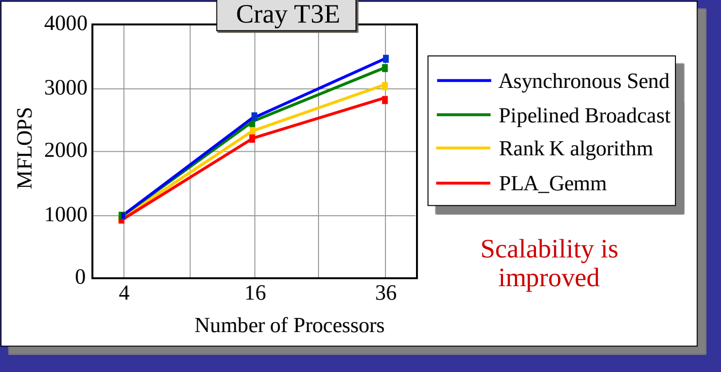
Improvement over clean, high quality PLAPACK programs

PLA_Trsm() and PLA_Gemm() are specialized for their specific calling contexts



A Closer Look at Gemm

- MPI_Send is specialized
- Broadcast is specialized
- The Gemm algorithm is specialized



Optimizing at Multiple Levels

Levels of Abstraction in PLAPACK

Global	global matrix operations	PLA_Gemm()
Explicitly parallel	matrices + high level communication	Rank K algorithm
Local	MPI + local BLAS	MPI_Send()
C language	C primitives	

Broadway

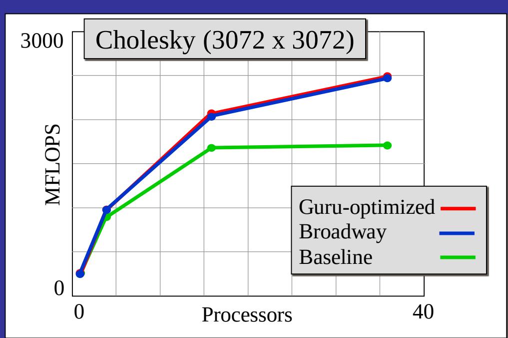
C compiler

There is great benefit to optimizing at multiple levels of abstraction

Ultimate Performance Comparison

Gold standard

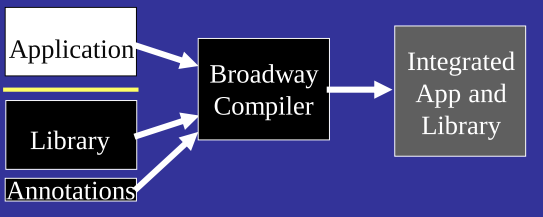
– Comparison against hand-optimized version written by PLAPACK development team



Optimization Summary

How did we improve performance?

– We specialized the library code for the specific context of the Cholesky application



Traditional compilers cannot exploit these opportunities

– They are unaware of domain-specific semantics

The specification can be simple

– The power is in the compiler mechanisms
– Data-flow analysis is a powerful tool

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Error Detection

Error detection is a significant problem

- Code review and testing are tedious and unreliable
- Can the compiler help us?

Problem

- Errors are often domain-specific
- Not errors in the base programming language

Solution

- Use Broadway configurable analysis capabilities

Motivating Example

Format string vulnerability

- Well-known error – many CERT advisories
- Improper use of `printf()` family
- Example:

```
fgets(buffer, size, file);
printf(buffer);
```

- What if the buffer contains “%s”?
- What if the buffer is passed to `sprintf()`?

General solution

- **Taintedness** analysis
- Data from untrusted sources is “tainted”
- Tainted data may not end up in format string

How do we track this property?

Previous Solutions– Type Qualifiers [Shankar, *et al* ’01]

Idea

– Add tainted and untainted types to library function signatures

```
fgets(tainted char *buffer, int size, FILE *f);
printf(untainted char *format, . . .);
```

– Use type constraint solver to find errors
  – Errors are type mismatches

Issues

– What is the type of `strdup()`?
– What happens when the value of strings change?

Results

Type qualifier approach

– Requires manual intervention to identify context-sensitivity

Program	Lines of C	Procedures	Known Errors	Errors Found	False Positives
bftpd	**1,017**	**180**	1	1	2
muh	**5,002**	**228**	1	1	12
cfengine	**45,102**	**700**	6	6	5
. . .					

Problem

– Type-based constraints are not context-sensitive
– Even a few false positives can be a problem

The Broadway Solution

Idea

– Track the taintedness of strings using dataflow analysis problem

Modeling format string vulnerabilities

– Define a taintedness lattice
– Determine the objects that carry the property
– Describe how library routines affect the property
– Identify the error conditions

Taintedness Lattice

```
property Taint : { Tainted { Untainted }}
```

($\top$)
Untainted
Tainted
($\bot$)

Generating Tainted Data

Any external input is tainted

– User input: **`scanf()`, `gets()`**
– External values: **`getenv`**`()`
– File input: **`read()`, `fscanf()`, `readdir()`**

```
procedure read(fd, buffer_ptr, size)
{
  on_entry { buffer_ptr → buffer }
  access { Disk }
  modify { buffer }
  analyze Taint { buffer <- Tainted }
}
```

Note:

– Taintedness is a property of the buffer, not the surface variable

Transmitting Taintedness

String manipulation can transmit taintedness

– Examples: `strdup()`, `strcpy()`, `strcat()`, `sprintf()`

```
procedure strcpy(dest, src)
{
   on_entry { src → src_string
              dest → dest_string
     }
   access { src_string }
   modify { dest_string }

   analyze Taint {
    if (src_string is-exactly Tainted)
      dest_string <- Tainted
    if (src_string is-exactly Untainted)
      dest_string <- Untainted
  }
}
```


Reporting Errors

Test the flow values

– Tainted strings are not allowed to be format strings

  – Examples: `printf()` family, `syslog()`

```
procedure syslog(priority, format_ptr, args)
{
  on_entry { format_ptr → format
             args → arg_contents }
  access { format, arg_contents }

  report if (Taint : format is-exactly Tainted)
    "Error at " ++ @context ++ ": Argument "
    ++ [ format_ptr ] ++ " is tainted.\n";
}
```

Report the exact location of the problem

– The `@context` token gives the full call stack

– Brackets are special tokens that represent the name of the actual argument

Program Checking with Broadway

Benchmarks

– Actual programs that were distributed with the bug

Program	Lines of C	Procedures	Analysis Time (min:sec)	Known Errors	Errors Found	False Positives
bftpd	**1,017**	**180**	**0:01**	1	1	0
muh	**5,002**	**228**	**0:06**	1	1	0
cfengine	**45,102**	**700**	**6:38**	6	6	0
named	**25,820**	**444**	**1:11**	1	1	0
lpd	**38,174**	**726**	**23:57**	1	1	0

Run on 2Ghz Pentium 4 with 512 MB RAM

Open Questions

How else can domain-specific information be useful?

– Scheduling and resource management optimizations
– Algebraic properties of operations
– Optimization of sequences of operations
– Machine-specific customization

Can we apply these ideas to object-oriented languages?

– Higher cost of encapsulation
– Extensible code is an issue

Can we apply these ideas to dynamic optimizations?

Conclusions: Compiler Perspective

Compilers typically do better with more information

- Increased scope
  - Peephole → Local → Global → Interprocedural analysis
- Dynamic information
  - Profiling
  - Dynamic feedback
- We've introduced a third, orthogonal dimension
  - Domain-specific information

Conclusions: Software Design

Generality vs. Performance Tradeoff

- Weak assumptions → generality, code reuse
- Strong assumptions → good performance

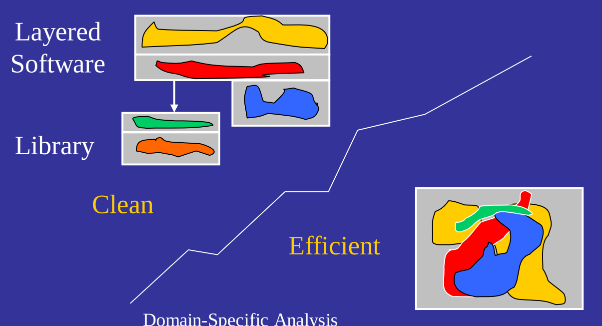
Breaking the tradeoff

- Programmers should create software that is general
- Let compilers specialize the software for specific contexts

Conclusions: Software Quality

Improving software quality

- To improve the quality software, raise the level of programming abstraction
- To help programmers reason at high levels, provide tools to reason at these high levels
- This idea applies to compilers, debuggers, performance analysis tools, *etc.*



Next Time

Lecture

- Adaptive pointer analysis

Projects

- Pre-proposals due tonight