CSE P503: Principles of Software Engineering

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Software tools & environments

The difference between a tool and a machine is not capable of very precise distinction…

--Charles Babbage

Tool vendors have made a good start, but have much work to do in tools that depend on compilers and other source code analyzers.

--Bjarne Stroustrop

Tonight

- Some historical background on programming environments and CASE
- A variety of tools and their underlying analysis

Some classic environments

- Interlisp
- Smalltalk-80
- Unix
- Cedar

Interlisp (Xerox PARC)

- Teitelman & Masinter, 1981
- Language-centered environment
- Very fast turnaround for code changes
- Monolithic address space
  - Environment, tools, application code commingled
- Code and data share common representation

Smalltalk-80 (Xerox PARC)

- Goldberg, 1984
- Language-centered environment (OO)
  - Classes as first-class objects, inheritance, etc.
- Environment structured around language features (class browsers, protocols, etc.)
- Rich libraries (data structures, UI, etc.)

Unix (Bell Labs)

- Toolkit-based environment
- Simple integration mechanism
  - Convenient user-level syntax for composition
- Standard shared representation
- Language-independent (although biased)
- Efficient for systems' programming

Cedar (Xerox PARC)

- Teitelman, 1984
- Intended to mix best features of Interlisp, Smalltalk-80, and Mesa
- Primarily was an improvement on Mesa
  - Language-centered environment
  - Abstract data type language
    - Strong language and environment support for interfaces
  - Key addition: garbage collection

Commercialization: a decade ago

- A decade ago, 22 companies matched “CASE” in Company Profiles database
  - About 10,000 matched “software”
  - 23 matched “application development”
- A decade ago, 3 Yahoo CASE categories
  - 55-60 registered CASE pages in Yahoo
  - (35 Java categories, thousands of pages)

The business of CASE

- IDE (Software through Pictures)
  - Founded 1983
  - Acquired by Thomson-CSF 1996
    - ~$10M annual sales
- Rational
  - Founded 1982
  - $572M sales in 2000
  - Acquired by IBM

The business of CASE

- Popkin
  - Founded 1986
    - ~$15M annual sales
- Cayenne Software, Inc. (1996)
  - Merger of Bachman (1983) and CADRE (1982)
    - ~$14M annual sales
    - Now out of business
- StructSoft (TurboCASE/Sys)
  - Formed 1984
    - ~$6M annual sales

The business of CASE

- I-Logix
  - Founded 1987
    - ~$10M annual sales
- Reasoning Systems
  - Founded 1984
    - ~$20M annual sales

CASE quotation I

- “Despite the many grand predictions of the trade press over the past decade, computer-assisted software engineering (CASE) tools failed to emerge as the promised `silver bullet.’”
  - – Guinan, Cooprider, Sawyer; IBM Systems Journal, 1997

CASE quotation II

- “CASE tools are sometimes excessively rigid in forcing the user to input too much information before giving usable results back. CASE tools also typically don't adapt to multiple or in-house methodologies…”
  – www.confluent.com; 1997

Tools

- The pendulum swings back and forth between integrated environments and tools
- In the mid-1990’s, the shift was to tools
- It is now back on environments: Eclipse, Visual Studio, etc…
  - It may remain here for lots of reasons

Programming language analysis

- The underlying premises and implementation structures for many tools and language implementations are closely related to programming language analysis
- Examples include:
  - The program dependence graph representation is heavily used in program optimization and parallelization, as well as in software engineering tools
  - Type inference is being used increasingly broadly as the basis for some software engineering tools
    - We'll see one concrete example, Lackwit

Type inferencing

- One downside of type systems is that the programmer has to write more “stuff”
- Type inferencing has the compiler compute what the types of the expressions should be
  - The programmer writes less down
  - The programmer has less to change when the program is modified
  - The programmer gets almost all the benefits of static typing

A classic static tool: slicing

- Of interest by itself
- And for the underlying representations
  - Originally, data flow
  - Later, program dependence graphs

Slicing, dicing, chopping

- Program slicing is an approach to selecting semantically related statements from a program [Weiser]
- In particular, a slice of a program with respect to a program point is a projection of the program that includes only the parts of the program that might affect the values of the variables used at that point
  - The slice consists of a set of statements that are usually not contiguous

Basic ideas

- If you need to perform a software engineering task, selecting a slice will reduce the size of the code base that you need to consider
- Debugging was the first task considered
  – Weiser even performed some basic user studies
- Claims have been made about how slicing might aid program understanding, maintenance, testing, differencing, specialization, reuse and merging

Example

```
read(n)
i := 1;
sum := 0;
product := 1;
while i <= n do begin
    sum := sum + i;
    product :=
      product * i;
    i := i + 1;
end;
write(sum);
write(product);
```

```
read(n)
i := 1;
sum := 0;
product := 1;
while i <= n do begin
    sum := sum + i;
    product :=
      product * i;
    i := i + 1;
end;
write(sum);
write(product);
```

This example (and other material) due in part to Frank Tip

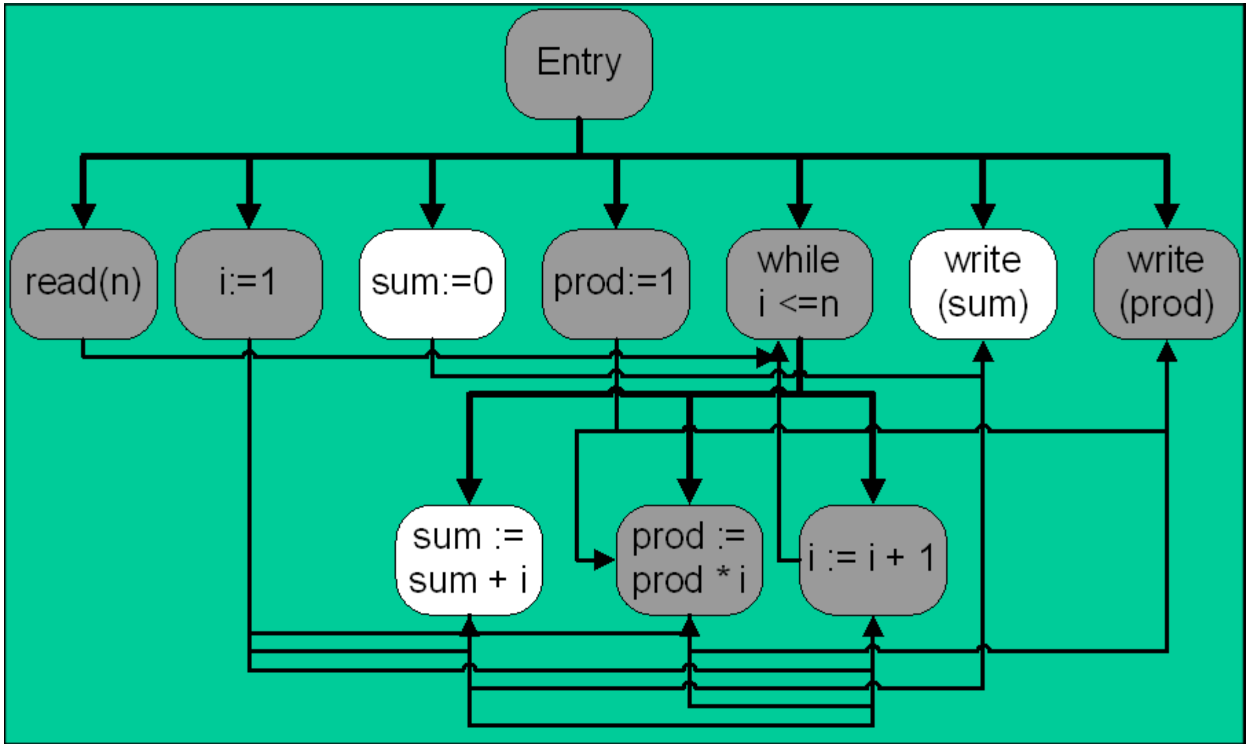
Weiser's approach

- For Weiser, a slice was a reduced, executable program obtained by removing statements from a program
  - The new program had to share parts of the behavior of the original
- Weiser computed slices using a dataflow algorithm, given a program point (criterion)
  - Using data flow and control dependences, iteratively add sets of relevant statements until a fixpoint is reached

Ottenstein & Ottenstein

- Build a program dependence graph (PDG) representing a program
- Select node(s) that identify the slicing criterion
- The slice for that criterion is the reachable nodes in the PDG

PDG for the example



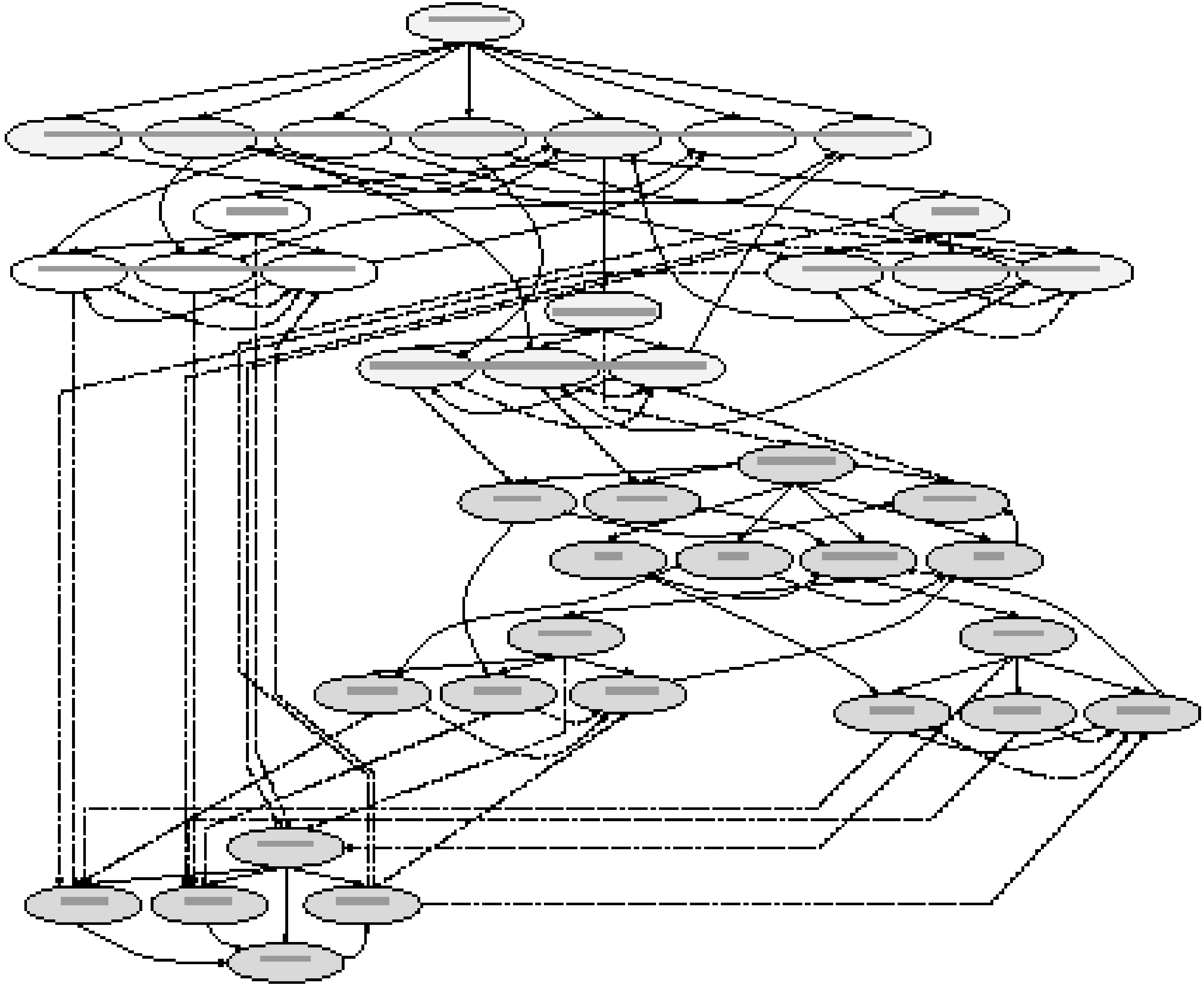
- Thick lines are control dependences
- Thin lines are (data) flow dependences

Procedures

- What happens when you have procedures and still want to slice?
- Weiser extended his dataflow algorithm to interprocedural slicing
- The PDG approach also extends to procedures
  - But interprocedural PDGs are a bit hairy (Horwitz, Reps, Binkley used SDGs)
  - Representing conventional parameter passing is not straightforward

The next slide...

- ..shows a very fuzzy version of the SDG for a version of the product/sum program
  – Procedures Add and Multiply are defined
  – They are invoked to compute the sum, the product and to increment i in the loop



Context

- A big issue in interprocedural slicing is whether context is considered
- In Weiser's algorithm, every call to a procedure could be considered as returning to any call site
  - This may significantly increase the size of a slice

Reps et al.

- Reps and colleagues have a number of results for handling contextual information for slices
- These algorithms generally work to respect the call-return structure of the original program
  - This information is usually captured as summary edges for call nodes

Technical issues

- How to slice in the face of unstructured control flow?
- Must slices be executable?
- What about slicing in the face of pointers?
- What about those pesky preprocessor statements?

LCLint [Evans et al.]

- [Material taken in part from a talk by S. Garland]
- Add some partial specification information to C code to
  - Detect potential bugs
  - Enforce coding style
- Versatile and lightweight
  - Incremental gain for incremental effort
  - Fits in with other tools

Detects potential bugs

- Specifications enable more accurate checks, messages
- Memory management a particular problem in the C language

Enforces coding style

- Abstraction boundaries
- Use of mutable and immutable types

LCLint Does Not

- Encourage programmer to write
  - Contorted code
  - Inefficient code
- Report only actual errors
- Report all errors
- Insist on reporting a fixed set of potential errors
  - Many options and control flags

Ex: Definition before Use

- Sample code…can annotate in several ways
  - `if (setVal(n, &buffer)) ...`
- Must `buffer` be defined before calling `setVal`?
  - Yes: `bool setVal(int d, char *val);`
  - No: `bool setVal(int d, out char *val);`
- Is `buffer` defined afterwards?
  - Yes: `bool setVal(...); {modifies *val;}`
  - Maybe: `bool setVal(...); {modifies nothing;}`
  - NO!: `bool setVal(...); {ensures trashed(val);}`

More Accurate Checks

- Conventional lint tools report
  - Too many spurious errors
  - Too few actual errors
- Because
  - Code does not reveal the programmer’s intent
  - Fast checks require simplifying assumptions
- Specifications give good simplifying assumptions

Abstraction Boundaries

- Client code should rely only on specifications
- Types can be specified as abstract
  - **immutable type** `date`**;**
    - `date nextDay(date d); { }`
  - **mutable type** `set`**;**
    - `void merge(set s, set t); {modifies s;}`
- LCLint detects
  - Inappropriate access to representation
    - Including use of `==`
  - Inappropriate choice of representation
    - E.g., for meaning of `=` (sharing)

Checking Abstract Types

- Specification: `set.lcl` contains the single line
  - `mutable type set;`
- Client code
  - ```
    #include "set.h"
    bool f(set s, set t) {
      if (s->size > 0) return (s == t);
      ...
    ```
- `> lclint set client.c`
  - ```
    client.c:4,7:
       Arrow access field of abstract type
             (set): s->size
    ```
  - ```
    client.c:5,13:
       Operands of == are abstract
             type (set):  s == t
    ```
    ```

Checking Side Effects

- Specification:
```
void set_insert (set s, int e)
     { modifies s;}
void set_union(set s, set t)
     { modifies s;}
```
- Code (in `set.c`) :
```
void set_union (set s, set t) {
    int i;
    for (i = 0; i < s->size; i++)
       set_insert(t, s->elements[i]);
    }
```
- Message:
  - `set.c:35, 27:`
```
      Called procedure set_insert may modify t:
         set_insert(t, s->elements[i])
```

Checking Use of Memory

- Specifications
  - ```
    only char *gname;
    . . .
    void setName (temp char *pname) char *gname;
    ```
- Code
  - ```
    void setName (char *pname) {
        gname = pname;
    }
    ```
- LCLint error messages
  - ```
    sample.c:2:3: Only storage gname not released
    before assignment:
        gname = pname
    ```
  - ```
    sample.c:2:3: Temp storage assigned to only:
    gname = pname
    ```

If C Were Better...

- Would LCLint still help?
- Yes, because specifications
  - contain information not in code
  - contain information that is hard to infer from code
  - are usable with legacy code, existing compilers
  - can be written faster than languages can be changed
  - are important even with better languages

Experience with LCLint

- Reliable and efficient
  - Runs at compiler speed
- Used on both new and legacy code
  - 1,000-200,000 line programs
  - Over 500 users have sent e-mail to MIT
- Tested with varying amounts of specification
  - Lots to almost none
  - LCLint approximates missing specifications
- Results encouraging

Understanding Legacy Code

- Analyzed interpreter (quake) built at DEC SRC
- Discovered latent bugs (ordinary lint can do this)
- Discovered programming conventions
  - Documented use of built-in types (int, char, bool)
  - Identified (and repaired) (nearly) abstract types
- Documented action of procedures
  - Use of global information, side-effects
- Enhanced documentation a common thread
  - Easier to read and write because formulaic
  - More trustworthy because checked

Fundamental benefit

- Partial specifications
- Low entry cost
- You get what you pay for (or maybe a bit more)

Lackwit (O'Callahan & Jackson)

- Code-oriented tool that exploits type inference
- Answers queries about C programs
  - e.g., "locate all potential assignments to this field"
  - Accounts for aliasing, calls through function pointers, type casts
- Efficient

Placement

- Lexical tools are very general, but are often imprecise because they have no knowledge of the underlying programming language
- Syntactic tools have some knowledge of the language, are harder to implement, but can give more precise answers
- Semantic tools have deeper knowledge of the language, but generally don’t scale, don’t work on real languages and are hard to implement

Lackwit

- Semantic
- Scalable
- Real language (C)
- Static
- Can work on incomplete programs
  - Make assumptions about missing code, or supply stubs

- Sample queries
  - Which integer variables contain file handles?
  - Can pointer `foo` in function `bar` be passed to `free()`? If so, what paths in the call graph are involved?
  - Field `f` of variable `v` has an incorrect value; where in the source might it have changed?
  - Which functions modify the `cur_veh` field of `map_manager_global`?

Lackwit analysis

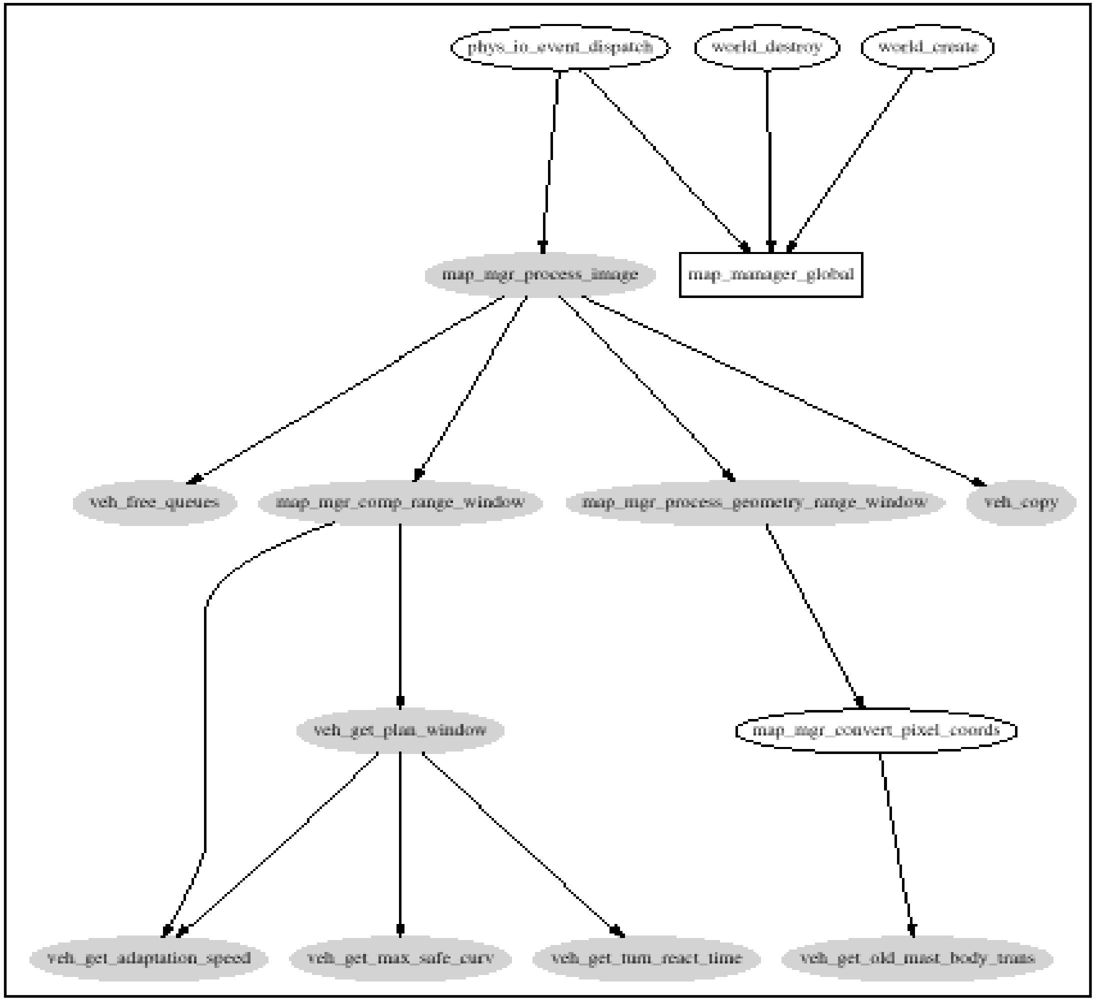
- Approximate (may return false positives)
- Conservative (may not return false negatives) under some conditions
  - C's type system has holes
  - Lackwit makes assumptions similar to those made by programmers (e.g., "no out-of-bounds memory accesses")
  - Lackwit is unsound only for programs that don't satisfy these assumptions

Query commonalities

- There are a huge number of names for storage locations
  - local and global variables; procedure parameters; for records, etc., the sub-components
- Values flow from location to location, which can be associated with many different names
- Archetypal query: Which other names identify locations to which a value could flow to or from a location with this given name?
  - Answers can be given textually or graphically

An example

- Query about the `cur_veh` field of `map_manager_global`
- Shaded ovals are functions extracting fields from the global
- Unshaded ovals pass pointers to the structure but don’t manipulate it
- Edges between ovals are calls
- Rectangles are globals
- Edges to rectangles are variable accesses



Claim

- This graph shows which functions would have to be checked when changing the invariants of the current vehicle object
  - Requires semantics, since many of the relationships are induced by aliasing over pointers

Underlying technique

- Use type inference, allowing type information to be exploited to reduce information about values flowing to locations (and thus names)
- But what to do in programming languages without rich type systems?

Trivial example

- `DollarAmt getSalary(EmployeeNum e)`
- Relatively standard declaration
- Allows us to determine that there is no way for the value of `e` to flow to the result of the function
  – Because they have different types

- `int getSalary(int e)`
- Another, perhaps more common, way to declare the same function
- This doesn't allow the direct inference that `e`'s value doesn't flow to the function return
  – Because they have the same type
- Demands type inference mechanism for precision

Lackwit's type system

- Lackwit ignores the C type declarations
- Computes new types in a richer type system

- `char* strcpy(char* dest,char* source)`
- $(\mathtt{num}^{\alpha}\ \mathtt{ref}^{\beta}, \mathtt{num}^{\alpha}\ \mathtt{ref}^{\gamma}) \to^{\phi} \mathtt{num}^{\alpha}\ \mathtt{ref}^{\beta}$
- Implies
  - –Result may be aliased with `dest` (flow between pointers)
  - –Values may flow between the characters of the parameters
  - –No flow between `source` and `dest` arguments (no aliasing)

Incomplete type information

- `void* return1st(void* x,void* y) {`
  `return x; }`
- $(a\ \mathbf{ref}^{\beta}, b) \rightarrow^{\phi} a\ \mathbf{ref}^{\beta}$

- The type variable *a* indicates that the type of the contents of the pointer `x` is unconstrained
  - But it must be the same as the type of the contents of pointer `y`
- Increases the set of queries that Lackwit can answer with precision

Polymorphism

- ```
  char* ptr1;
  struct timeval* ptr2;
  char** ptr3;
  …
  return1st(ptr1,ptr2); return1st(ptr2,ptr3)
  ```
- Both calls match the previous function declaration
- This is solved (basically) by giving `return1st` a richer type and instantiating it at every call site
  - $(c\ \mathbf{ref}^{\beta},\ d) \to^{\delta} c\ \mathbf{ref}^{\beta}$
  - $(e\ \mathbf{ref}^{\alpha},\ f) \to^{\chi} e\ \mathbf{ref}^{\alpha}$
  ```

Type stuff

- Modified form of Hindley-Milner algorithm “W”
- Efforts made to handle
  - Mutable types
  - Recursive types
  - Null pointers
  - Uninitialized data
  - Type casts
  - Declaration order

```
void copy(char * from, char * to) {
    *to = *from;
}
void copy5(char * fromarray, char * toarray) {
    int i;
    for (i = 0; i < 5; i++) {
        copy(from + i, to + i);
    }
}
void main(void) {
    char from1[5] = { 'h', 'e', 'l', 'l', 'o' };
    char to1[5];
    char from2[5] = { 'k', 'i', 't', 't', 'y' };
    char to2[5];
    copy5(from1, to1);
    copy5(from2, to2);
```

`copy`	$\forall\alpha.\forall\beta.\forall\phi.(\mathrm{num}^{\alpha}\ \mathrm{ref}^{\beta}, \mathrm{num}^{\alpha}\ \mathrm{ref}^{\chi}) \to^{\phi} ()$
`copy5`	$\forall\delta.\forall\varphi.\forall\sigma.(\mathrm{num}^{\delta}\ \mathrm{ref}^{\varphi}, \mathrm{num}^{\delta}\ \mathrm{ref}^{\kappa}) \to^{\sigma} ()$
`main:from1`	$\mathrm{num}^{\theta}\ \mathrm{ref}^{\varphi}$
`main:to1`	$\mathrm{num}^{\theta}\ \mathrm{ref}^{\eta}$
`main:from2`	$\mathrm{num}^{\mu}\ \mathrm{ref}^{\zeta}$
`main:to2`	$\mathrm{num}^{\mu}\ \mathrm{ref}^{\gamma}$

- `*from1` is not compatible with either `*from2` or `*to2`
  - But it is with `copy:*from`, `copy:*to`, `copy5:*from` + `copy5:*to`

Program invariants

- One way to try to manage the complexity of software systems is to use program invariants
- Invariants can aid in the development of correct programs
  - The invariants are defined explicitly as part of the construction of the program [Dijkstra][Hoare][Gries][…]

Invariants and evolution

- Invariants can aid in the evolution of software as well
- In particular, programmers can easily make changes that violate unstated invariants
  - The violated invariants are often far from the site of the change
  - These changes can cause errors
  - The presence of invariants can reduce the number of or cost of finding these violations

Other uses for invariants

- Documenting code
- Checking assumptions: convert to assert
- Locating unusual conditions
- Providing hints for higher-level profile-directed compilation [Calder]
- Bootstrapping proofs [Wegbreit][Bensalem]
- …

Today's focus

- An approach to make invariants more prevalent and more practical
- Underlying assumption:
  - The presence of invariants will reduce the difficulty and cost of evolution
- Goal: recover invariants from programs
- Technique: run the program, examine values
- Artifact: Daikon

Goal: Recover invariants

- Detect invariants such as those found in assert statements or specifications
  - *x > abs(y)*
  - *x = 16*y + 4*z + 3*
  - *array a contains no duplicates*
  - *for each node n, n = n.child.parent*
  - *graph g is acyclic*
  - *…*

Experiment 1 [Gries 81]:

Recover formal specifications

```
// Sum array b of length n into
// variable s
i := 0; s := 0;
while i ≠ n do
  { s := s+b[i];  i := i+1 }
```

Precondition: $n \geq 0$

Postcondition: $S = \Sigma_{0 \leq j < n} b[j]$

Loop invariant:

$$0 \leq i \leq n \text{ and } S = \Sigma_{0 \leq j < i} b[j]$$

Test suite

- 100 randomly-generated arrays
  - length uniformly distributed from 7 to 13
  - elements uniformly distributed from –100 to 100
- First guess for a test suite
  - Turned out to work well
  - More on test suites later on

Inferred invariants

```
ENTRY:
    N = size(B)
    N in [7..13] ♦
    B: All elements in [-100..100]
EXIT:
    N = I = orig(N) = size(B)
    B = orig(B)
    S = sum(B) ♦
    N in [7..13]
    B: All elements in [-100..100]
```

Inferred loop invariants

```
LOOP:
    N = size(B)
    S = sum(B[0..I-1]) ♦
    N in [7..13]
    I in [0..13] ♦
    I <= N ♦
    B: All elements in [-100..100]
    B[0..I-1]: All elements in [-100..100]
```

Experiment 2:
Code without explicit invariants

- 563-line C program: regular expression search & replace [Hutchins][Rothermel]
- Task: modify to add Kleene +
- Complementary use of both detected invariants and traditional tools (such as grep)

Programmer use of invariants

- Helped explain use of data structures
  - regexp compiled form (a string)
- Contradicted some maintainer expectations
  - anticipated *lj* < *j* in `makepat`
  - queried for counterexample
  - avoided introducing a bug
- Revealed a bug
  - when *lastj* = **j* in `stclose`, array bounds error

More invariant uses

- Showed procedures used in limited ways
  - `makepat`
    start = 0 and *delim = '\0'*
- Demonstrated test suite inadequacy
  - *#calls(in_set_2) = #calls(stclose)*
- Changes in invariants validated program changes
  - `stclose`: $*j = orig(*j)+1$
  - `plclose`: $*j \geq orig(*j)+2$

Experiment 2 conclusions

- Invariants
  - effectively summarize value data
  - support programmer’s own inferences
  - lead programmers to think in terms of invariants
  - provide serendipitous information
- Additional useful components of Daikon
  - trace database (supports queries)
  - invariant differencer

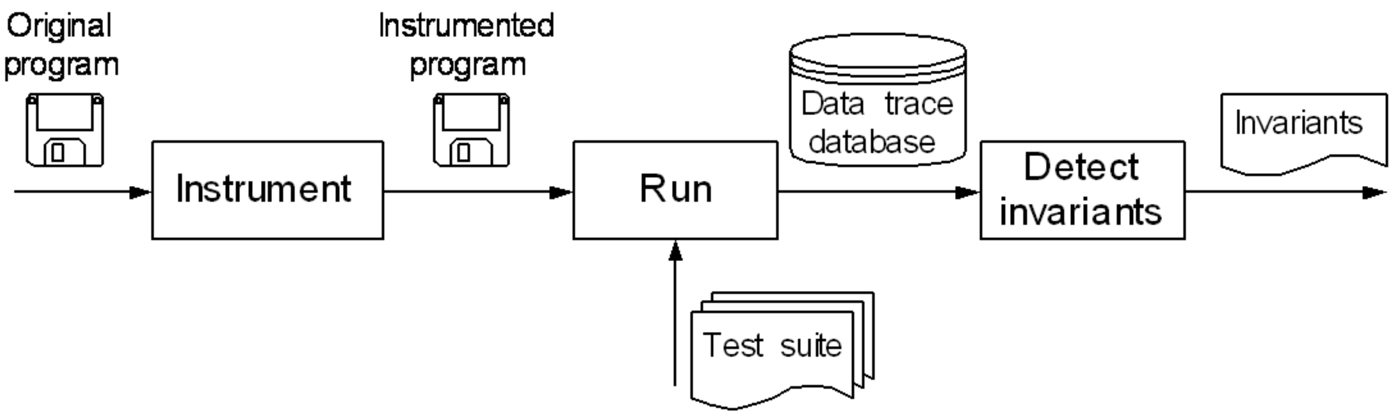
Other experiments

- Students
  - –UW CSE 142 (C, small)
  - –MIT 6.170 (Java, ≤ 5000 lines)
- Testing research
  - –Hoffman (Java, 2000 lines)
  - –Siemens (C, ~500 lines)
- Program checkers
  - –Xi (Java, small)
  - –ESC (Java, 500 lines)
- Textbooks
  - –Gries (Lisp, tiny)
  - –Weiss (Java, small)
  - –Java in a Nutshell (Java, ≤ 300 lines)
- Medic planner (Lisp, 13,000 lines)

Ways to obtain invariants

- Programmer-supplied
- Static analysis: examine the program text [Cousot][Gannod]
  - properties are guaranteed to be true
  - pointers are intractable in practice
- Dynamic analysis: run the program
  - complementary to static techniques

Dynamic invariant detection



- Look for patterns in values the program computes
  - –Instrument the program to write data trace files
  - –Run the program on a test suite
  - –Invariant engine reads data traces, generates potential invariants, and checks them
- Roughly, machine learning over program traces

Running the program

- Requires a test suite
  – Standard test suites are adequate
  – Relatively insensitive to test suite (if large enough)
- No guarantee of completeness or soundness
  – Useful nonetheless (cf. Purify, ESC, PREfix)
  – Complementary to other techniques and tools

Sample invariants

- *x,y,z* are variables; *a,b,c* are constants
- Invariants over numbers
  - unary: $x = a$, $a \leq x \leq b$, $x \equiv a (mod\ b)$, …
  - n-ary: $x \leq y$, $x = ay + bz + c$,
    $x = max(y, z)$, …
- Invariants over sequences
  - unary: sorted, invariants over all elements
  - with sequence: subsequence, ordering
  - with scalar: membership
- Why these invariants?

Checking invariants

- For each potential invariant:
  - Instantiate
    - That is, determine constants like a and b in $y = ax + b$
  - Check for each set of variable values
  - Stop checking when falsified
- This is inexpensive
  - Many invariants, but each cheap to check
  - Falsification usually happens very early

Performance: runtime growth

- Cubic in number of variables at a program point
  - Linear in number of invariants checked/discovered
- Linear in number of samples (test suite size)
- Linear in number of instrumented program points

Relevance

- Our first concern in this research was whether we could find *any* invariants of interest
- When we found we could, we found a different problem
  - We found many invariants of interest
  - But *most* invariants we found were not relevant

Improved invariant relevance

- Add desired invariants
  - Implicit values
  - Unused polymorphism
- Eliminate undesired invariants (and improve performance)
  - Unjustified properties
  - Redundant invariants
  - Incomparable variables

1. Implicit values

Find relationships over non-variables

- array: *length, sum, min, max*
- array and scalar: element at index, subarray
- number of calls to a procedure
- …

Derived variables

- Successfully produces desired invariants
- Adds many new variables
  - slowdown
  - irrelevant invariants
- Staged derivation and invariant inference
  - avoid deriving meaningless values
  - avoid computing tautological invariants

2. Unused polymorphism

- Variables declared with general type, used with more specific type
  - Ex: given a generic list that contains only integers, report that the contents are sorted
- Also applicable to subtype polymorphism

Unused polymorphism example

```
class MyInteger { int value; … }
class Link { Object element; Link next; … }
class List { Link header; … }
List myList = new List();
for (int i=0; i<10; i++)
  myList.add(new MyInteger(i));
```

- Desired invariant in class `List`
  - **`header.closure(next).element.value: sorted by ≤`**

Polymorphism elimination

- Pass 1: front end outputs object ID, runtime type, and all known fields
- Pass 2: given refined type, front end outputs more fields

- Effective for programs tested so far
- Sound for deterministic programs

3. Unjustified properties

- Given three samples for `x`:
  - **`x = 7`**
  - **`x = -42`**
  - **`x = 22`**

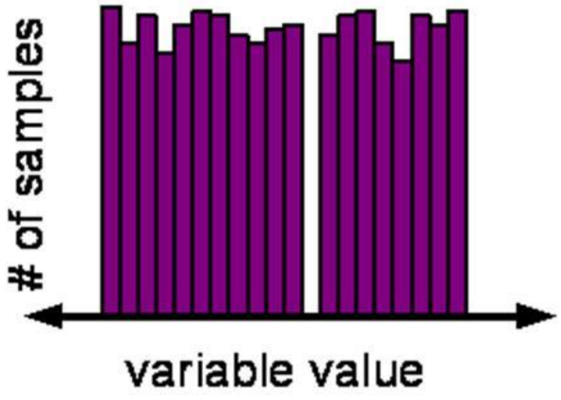
- Potential invariants:
  - **x ≠ 0**
  - **x ≤ 22**
  - **x ≥ -42**

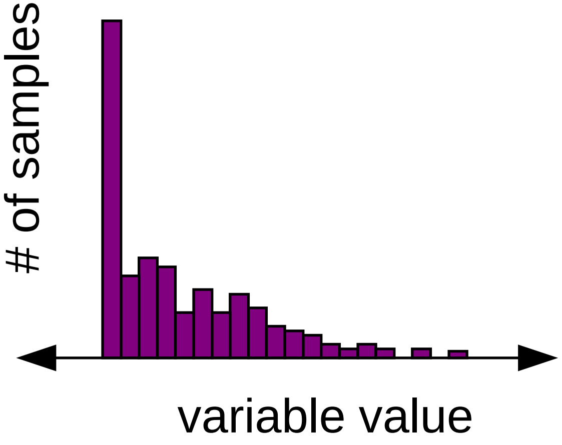
Statistical checks:
check hypothesized distribution

- Probability of no zeroes (to show $x \neq 0$) for v values of x in range of size r

$$\left(1-\frac{1}{r}\right)^{v}$$

- Range limits (e.g., $x \leq 22$)
  - same number of samples as neighbors (uniform)
  - more samples than neighbors (clipped)





Duplicate values

- Array sum program:

```
i := 0; s := 0;
while i ≠ n do
  { s := s+b[i]; i := i+1 }
```

- *b* is unchanged inside loop
- Problem: at loop head

  $-88 \leq b[n-1] \leq 99$

  $-556 \leq sum(b) \leq 539$
- Reason: more samples inside loop

Disregard duplicate values

- Idea: count a value only if its var was just modified
- Front end outputs modification bit per value
  - compared techniques for eliminating duplicates
- Result: eliminates undesired invariants

4. Redundant invariants

- Given
  $0 \leq i \leq j$
- Redundant
  $a[i] \in a[0..j]$
  $\max(a[0..i]) \leq \max(a[0..j])$

- Redundant invariants are logically implied
- Implementation contains many such tests

Suppress redundancies

- Avoid deriving variables: suppress 25-50%
  - equal to another variable
  - nonsensical
- Avoid checking invariants:
  - false invariants: trivial improvement
  - true invariants: suppress 90%
- Avoid reporting trivial invariants: suppress 25%

5. Unrelated variables

```
bool p;
int *p;
```

b < p

```
int myweight, mybirthyear;
```

myweight < mybirthyear

Limit comparisons

- Check relations only over comparable variables
  - declared program types
  - Lackwit [O'Callahan]

Comparability results

- Comparisons:
  - declared types: 60% as many comparisons
  - Lackwit: 5% as many comparisons; scales well
- Runtime: 40-70% improvement
- Few differences in reported invariants

Richer types of invariant

- Object/class invariants
  - **`node.left.value < node.right.value`**
  - **`string.data[string.length] = '\0'`**
- Pointers (recursive data structures)
  - **`tree is sorted`**
- Conditionals
  - ```
    if  proc.priority < 0 then
        proc.status = active
    ```
  - **`ptr = null  or  *ptr > i`**
    ```

Pointer experiment

- Data structures from Weiss's *Data Structures and Algorithm Analysis in Java*
- Identified goal invariants by reading book
- Added linearization and data splitting to Daikon
- Results
  - 90-100% of goal invariants
  - few extraneous invariants

Object invariant

- `class LinkedList { Link header; … }`
- `class Link { int element; Link next; … }`

- Object invariant:
  - **header ≠ null**
  - **header.element = 0**
  - **size(header.closure(next)) ≥ 1**

Conditional pointer invariant

- At exit of
  `LinkedList.insert(Object x, LinkedListItr p)`

- **`if (p ≠ null and p.current ≠ null) then`**
  `size(header.closure(next)) =`
- **`    size(orig(header.closure(next))) + 1`**
- **`else`**
  `header.closure(next)) =`
  `  orig(header.closure(next))`

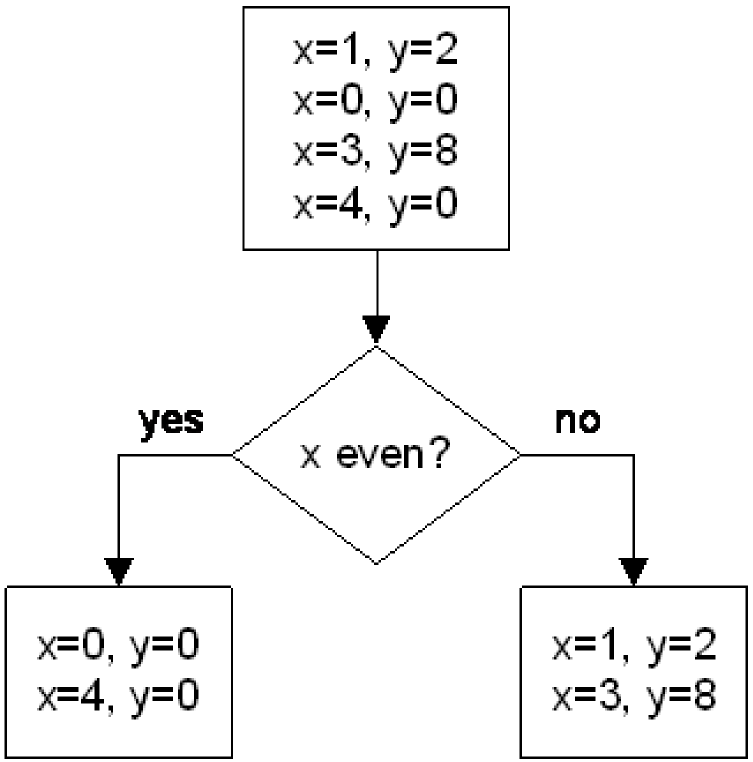
Linearize data structures

- Traverse pointer-directed data structures
- Present to invariant engine as sequence
  - cyclicity determined by front end

Conditionals: mechanism

- 1. Split the data into parts
- 2. Compute invariants over each subset of data
- 3. Compare results, produce implications

```
if even(x) then
  y = 0
else
  y = 2x
```



Data splitting criteria

- Static analysis
- Distinguished values: zero, source literals, mode, outliers, extrema
- Exceptions to detected invariants
- User-selected
- Exhaustive over random sample

Scaling

- Technology
  - many program points
  - large data structures
  - solution: next slide
- Utility
  - many program points
  - different invariants
  - different uses
  - solution: experiments, case studies

Incremental inference

- Online algorithm improves
  - response time
  - space
  - front end computation
  - back end computation
- Process each variable value once, then discard
- Stop checking invariants after falsification
- To do: selectively disable instrumentation

Summary

- Dynamic invariant detection is feasible
  - Conceived and developed the idea
  - Prototype implementation
- Dynamic invariant detection is accurate & useful
  - Techniques to improve basic approach
  - Experiments provide preliminary support
- Dynamic invariant detection is a challenging and promising area for research and practice
- See Ernst's web site at MIT for *lots* more

Path Profiling: Ball and Larus

```
#include <stdio.h>
main(t,_,a)
char *a;
{
return!0<t?t<3?main(-79,-13,a+main(-87,1-_,main(-86,0,a+1)+a)):
1,t<_?main(t+1,_,a):3,main(-94,-27+t,a)&&t==2?_<13?
main(2,_+1,"%s %d %d\n"):9:16:t<0?t<-72?main(_,t,
"@n'+,#'/*{}w+/w#cdnr/+,{}r/*de}+,/*{*+,/w{%+,/w#q#n+,/#{l+,/n{n+,/+#n+,/#\
;#q#n+,/+k#;*+,/'r :'d*'3,}{w+K w'K:'+}e#';dq#'l \
q#'+d'K#!/+k#;q#'r}eKK#}w'r}eKK{nl]'/#;#q#n'){)#}w'){){nl]'/+#n';d}rw' i;#\
){nl]!/n{n#'; r{#w'r nc{nl]'/#{l,+'K {rw' iK{;[{nl]'/w#q#n'wk nw' \
iwk{KK{nl]!/w{%'l##w#' i; :{nl]'/*{q#'ld;r'}{nlwb!/*de}'c \
;;{nl'-{}rw]'/+,}##'*}#nc,',#nw]'/+kd'+e}+;#'rdq#w! nr'/ ') }+}{rl#'{n' ')# \
}'+}##(!!/")
:t<-50?_==*a?putchar(31[a]):main(-65,_,a+1):main((*a=='/')+t,_,a+1)
:0<t?main(2,2,"%s"):*a=='/'||main(0,main(-61,*a,
"!ek;dc i@bK'(q)-[w]*%n+r3#l,{}:\nuwloca-O;m .vpbks,fxntdCeghiry"),a+1);
}
```

What does it do?
Run it!

- `On the first day of Christmas my true love gave to me`
  `a partridge in a pear tree.`
- `On the second day of Christmas my true love gave to me`
  `two turtle doves`
  `and a partridge in a pear tree.`
- `On the third day of Christmas my true love gave to me`
  `three french hens, two turtle doves`
  `and a partridge in a pear tree.`

  `...`

- But why?
  - http://www.research.microsoft.com/~tball/papers/XmasGift/
  - Reverse engineering the Twelve Days of Christmas

Counting arguments

- The poem takes O(N*N) time to read and O(N*N) space to write
  - N is the number of gifts
- We can derive an exact count of the number of times gifts
- A gift with ordinal value t is mentioned 13-t times in the poem
  - For example, "five gold rings" occurs 13-5=8 times
- Summing over all gifts yields 1+2+...11+12 = 13*6 = 78 total gift mentions
  - 66 mentions of non-partridge gifts

Continuing like this…key numbers are

- 12 days of Christmas (also 11, to catch "off-by-one" cases)
- 26 unique strings
- 66 occurrences of non-partridge-in-a-pear-tree presents
- 114 strings printed
- 2358 characters printed

Pretty printing the program...

```
/* pretty-printed version of twelve days of christmas program */
#include <stdio.h>
main(t,_,a)
char *a;
{
  return
    ((!0) < t )
      ? ((t < 3
          ? main(-79,-13,a+main(-87,1-_,main(-86,0,a+1)+a))
          : 1),

         (t < _
          ? main(t+1,_,a)
          : 3),

         (main(-94,-27+t,a)
          && (t==2
              ? ( _ < 13
                  ? main(2,_+1,"%s %d %d\n")
                  : 9)
              : 16)))

        : (t < 0
           ? (t < -72
              ?
```

Structure of the program

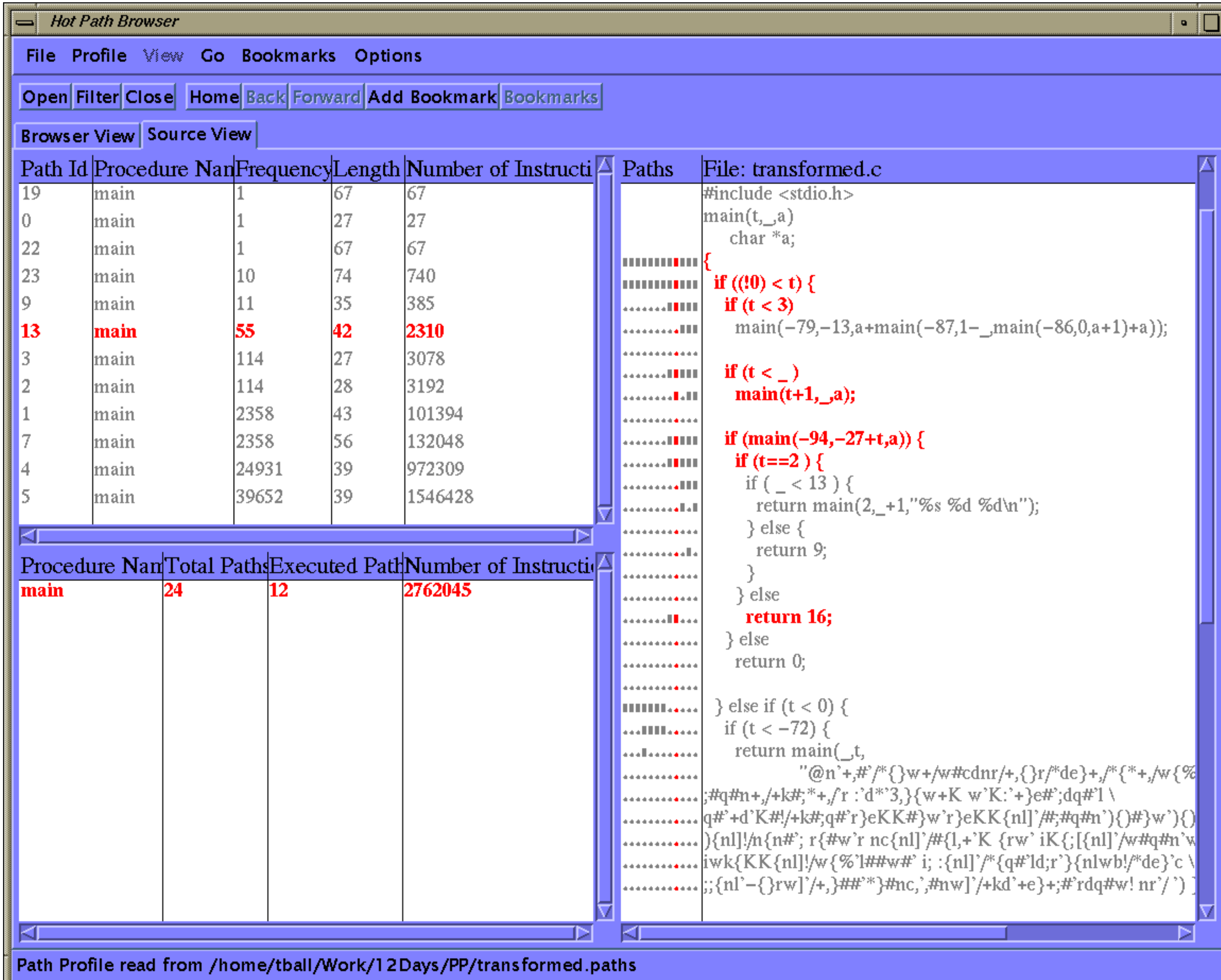
- After some pretty easy work, the program consists of just `main`
  - Calls itself repeatedly
    - No loops, only recursion
  - No assignments to any variables
  - Two large strings appear to encode the text of the poem

main: three arguments

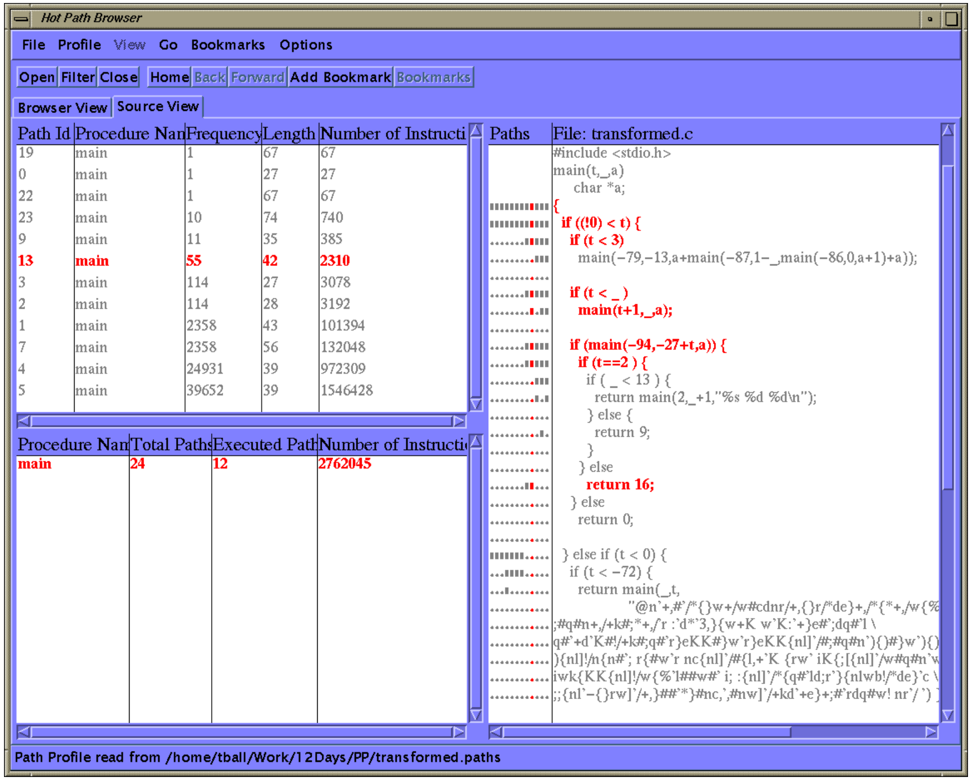
- The first argument t is count of the number of arguments on the command line (including the name of the program itself)
- The selection of different legs of the function seem to be driven by the parameter t

Use profiling to extract counts

- Apply the Hot Path Browser (HPB) tool (Ball, Larus and Rosay)
  - Instruments programs to record and display Ball/Larus path profiles
  - A Ball/Larus path profile counts how many times each acyclic intraprocedural path executes


Hot Path Browser
File Profile View Go Bookmarks Options
Open Filter Close Home Back Forward Add Bookmark Bookmarks
Browser View Source View
Path Id | Procedure Nan | Frequency | Length | Number of Instructi
19 main 1 67 67
0 main 1 27 27
22 main 1 67 67
23 main 10 74 740
9 main 11 35 385
13 main 55 42 2310
3 main 114 27 3078
2 main 114 28 3192
1 main 2358 43 101394
7 main 2358 56 132048
4 main 24931 39 972309
5 main 39652 39 1546428
Procedure Nan | Total Paths | Executed Path | Number of Instructi
main 24 12 2762045
Paths
File: transformed.c
#include <stdio.h>
main(t,_,a)
char *a;
{
if ((!0) < t) {
if (t < 3)
main(−79,−13,a+main(−87,1−_,main(−86,0,a+1)+a));
if (t < _)
main(t+1,_,a);
if (main(−94,−27+t,a)) {
if (t==2) {
if (_ < 13) {
return main(2,_+1,"%s %d %d\n");
} else {
return 9;
}
} else
return 16;
} else
return 0;
} else if (t < 0) {
if (t < −72) {
return main(_t,
"@n'+,#'/*{}w+/w#cdnr/+,{}r/*de}+,/*{*+,/w{%
;#q#n+,/+k#;*+,/r :'d*'3,}{w+K w'K:'+}e#';dq#'l \
q#'+d'K#!/+k#;q#'r}eKK#}w'r}eKK{nl]'/#;#q#n'){)#}w'){}
){nl]!/n{n#'; r{#w'r nc{nl]'/#{l,+'K {rw' iK{;[{nl]'/w#q#n'w
iwk{KK{nl]!/w{%'l##w#' i; :{nl]'/*{q#'ld;r'}{nlwb!/*de}'c \
;;{nl'−{}rw]'/+,}##'*}#nc,',#nw]'/+kd'+e}+;#'rdq#w! nr'/ ') }
Path Profile read from /home/tball/Work/12Days/PP/transformed.paths

- The upper left pane shows the statistics about each executed path
- 12 out of a total of 24 possible paths executed
- The paths listed in ascending order of frequency
- The path with id 13 has been selected (red line) and highlighted in the source code view



Path clusters by frequency:
manually identify computational signature

- Path 0 initializes the recursion with the call main(2,2,...)
- Paths 19, 22, and 23 control the printing of the 12 verses
  - Path 19 represents the first verse
  - Path 23 the middle 10 verses
  - Path 22 the last verse
  - The sum of these paths' frequencies is 12
  - The browser can help show that each of the paths covers a different set of recursive calls to main
- Paths 9 and 13 control the printing of the non-partridge-gifts within a verse
  - The frequencies of the two paths sum to 66

More

- Paths 2 and 3 print out a string
  - Each path has frequency 114, the exact number of strings predicted by our model
- Paths 1 and 7 print out the characters in a string
  - Each path executes 2358 times
- Paths 4 and 5 with the large and unusual frequencies of 24931 and 39652?
  - Path 4 skips over n sub-strings in the large string
    - Every time a sub-string is printed, a linear search through the text string is done to find the string
  - Path 5 linearly scans — for each character to be printed — the string that encodes the character translation to find the character that matches the current character to be printed

Jinsight: De Pauw, Sevitsky, et al. (IBM)

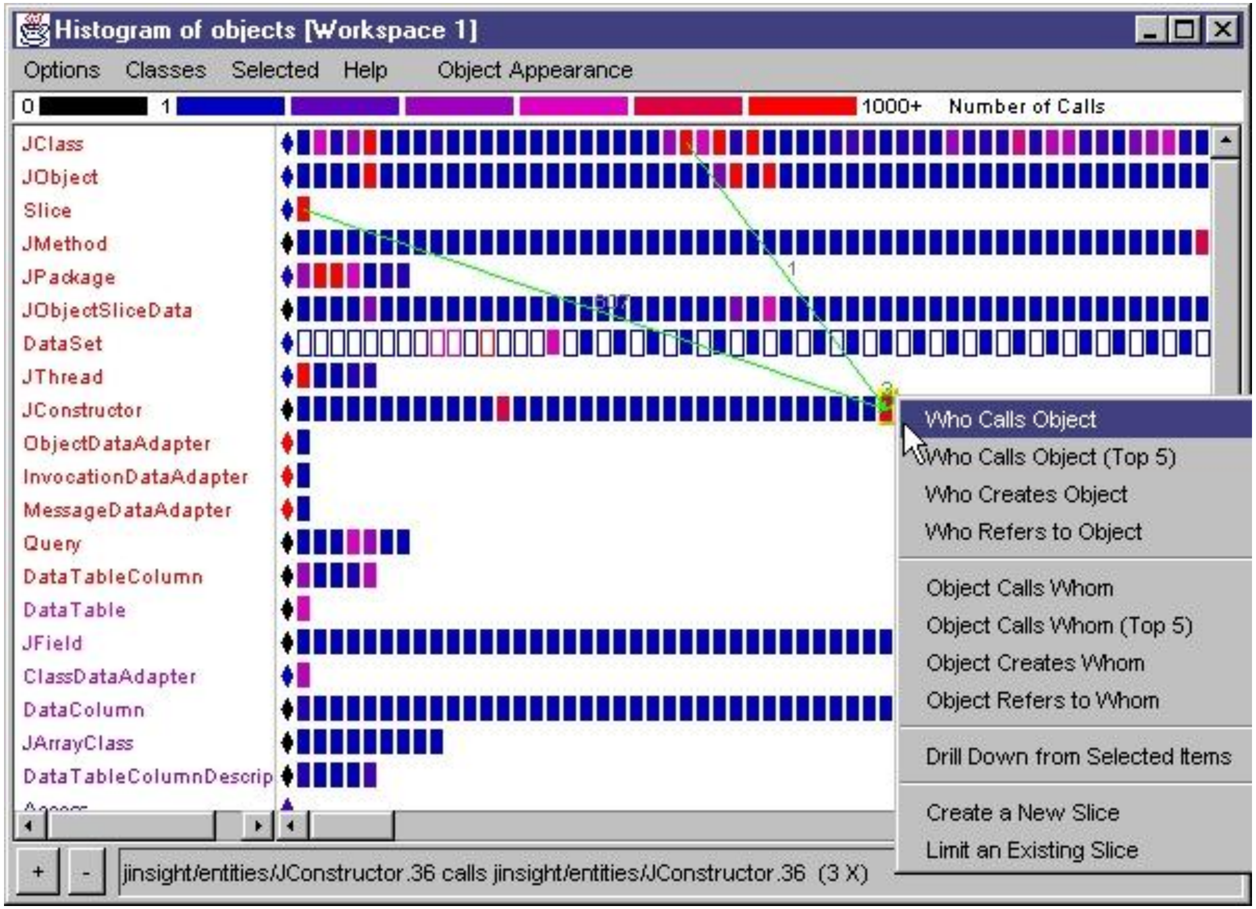
- Tools for analyzing the dynamic behavior of Java programs
  - Visualization
  - Pattern extraction
  - Database query
  - Multidimensional analysis
- Applied to
  - performance analysis
  - memory leak diagnosis
  - debugging
  - program understanding
- A special focus on the analysis of large, complex, data-intensive, and web-based systems

Tasks

- Visualizations of object usage, garbage collection and the sequence of activity in each thread
- Pattern visualizations extract structure in repetitive calling sequences and complex data structures
  - Analyze large amounts of information in a concise form
- Information exploration
  - Specify filtering criteria
  - Drill down from one view to another to explore details
  - Create units that match features of study
- Measurement
  - Execution activity or memory summarized at any level of detail, along call paths, and along two dimensions simultaneously

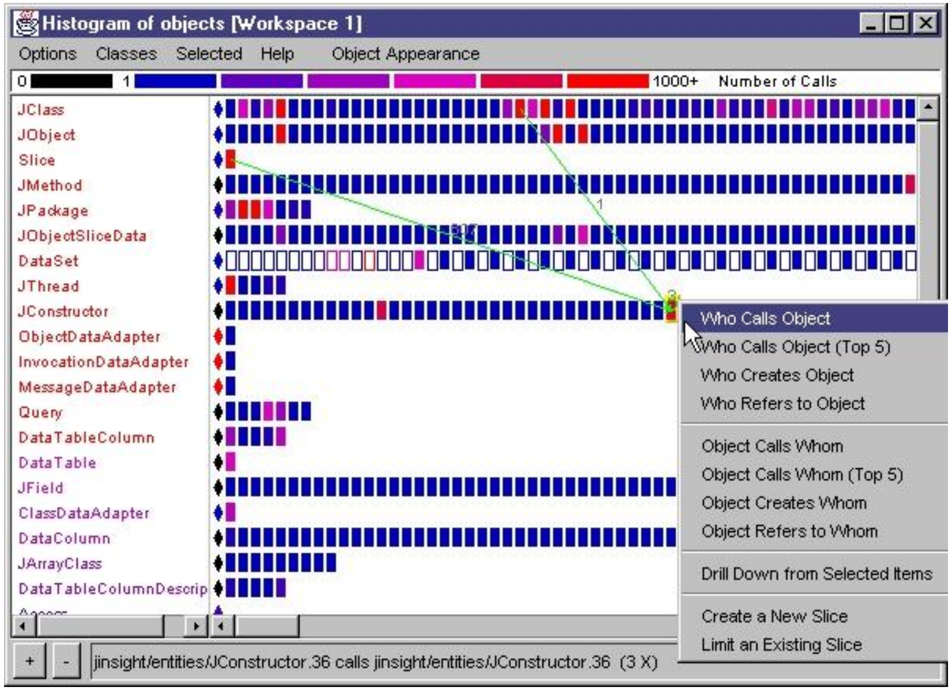
Object histogram view:

instances grouped by class, indicating level of activity



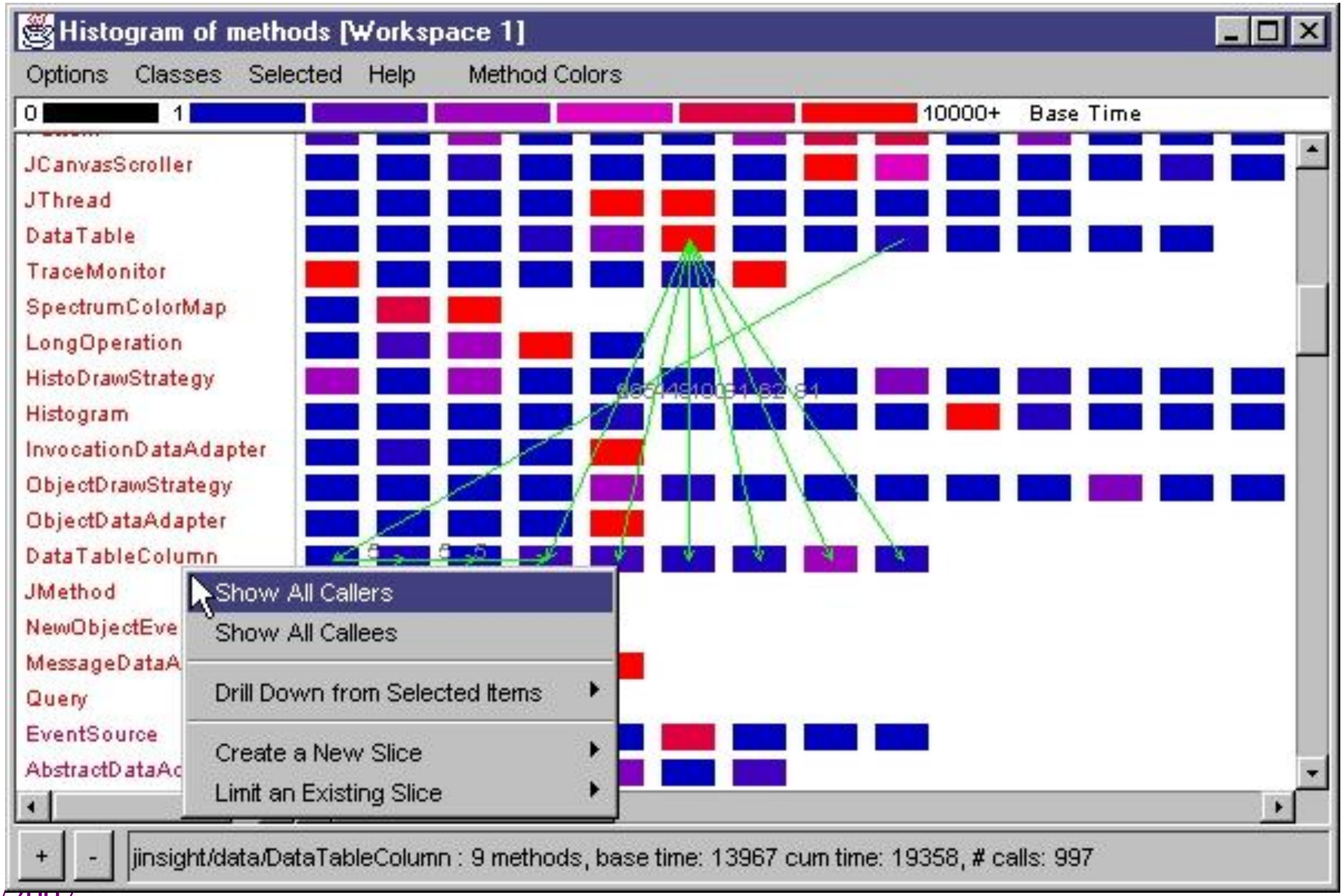
Object histogram view

- Class names along the left edge
- Each rectangle denotes an instance of that class or the amount of memory consumed by instances of the class
- A diamond shape denotes the class object for a given class
- A rectangle's color will vary according to a black-to-blue-to-red color spectrum
- Garbage collected objects appear as rectangular outlines

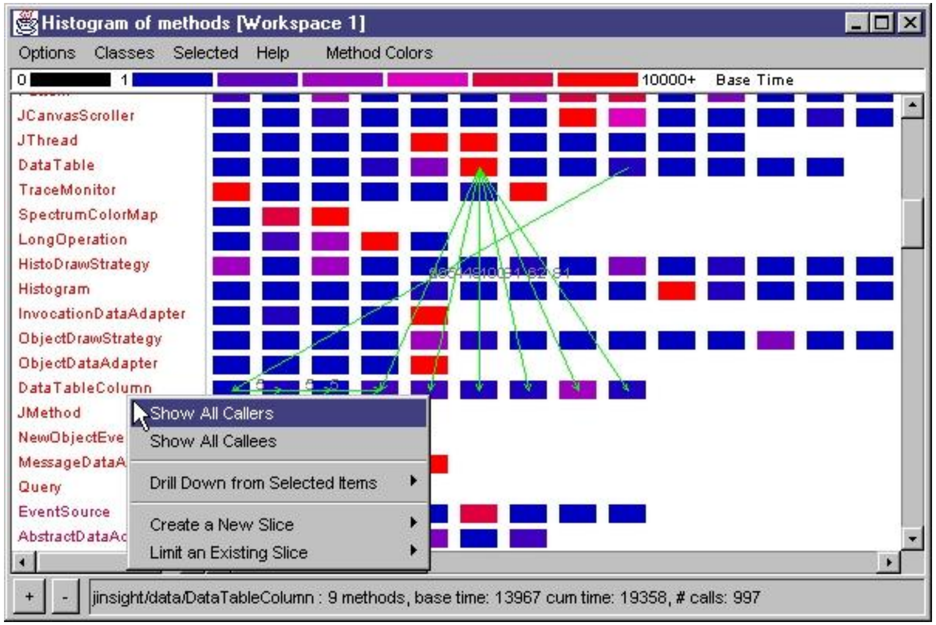


Method histogram view: methods grouped by class

•

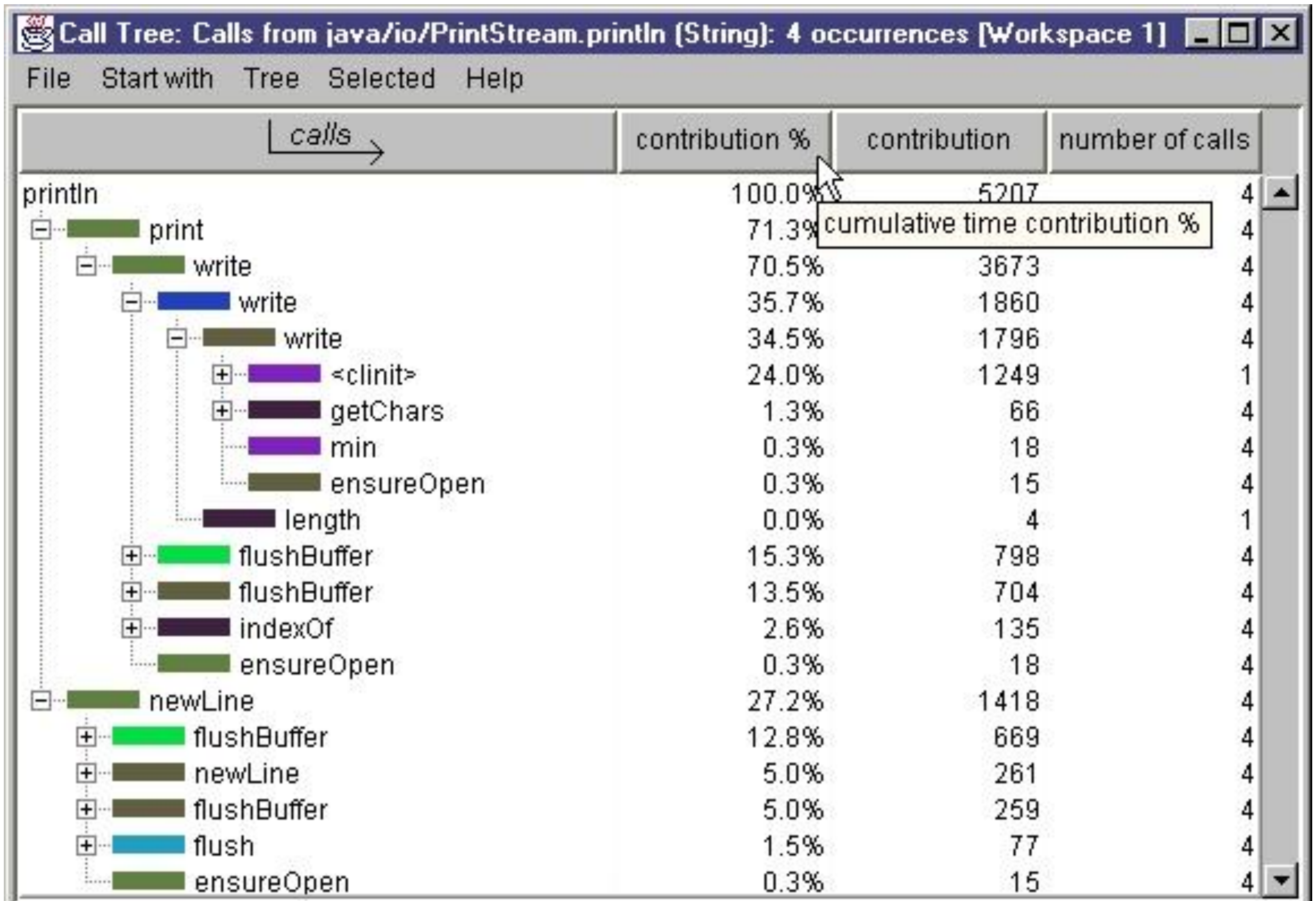


- Class names along the left edge
- Rectangles represent method of the class to its left



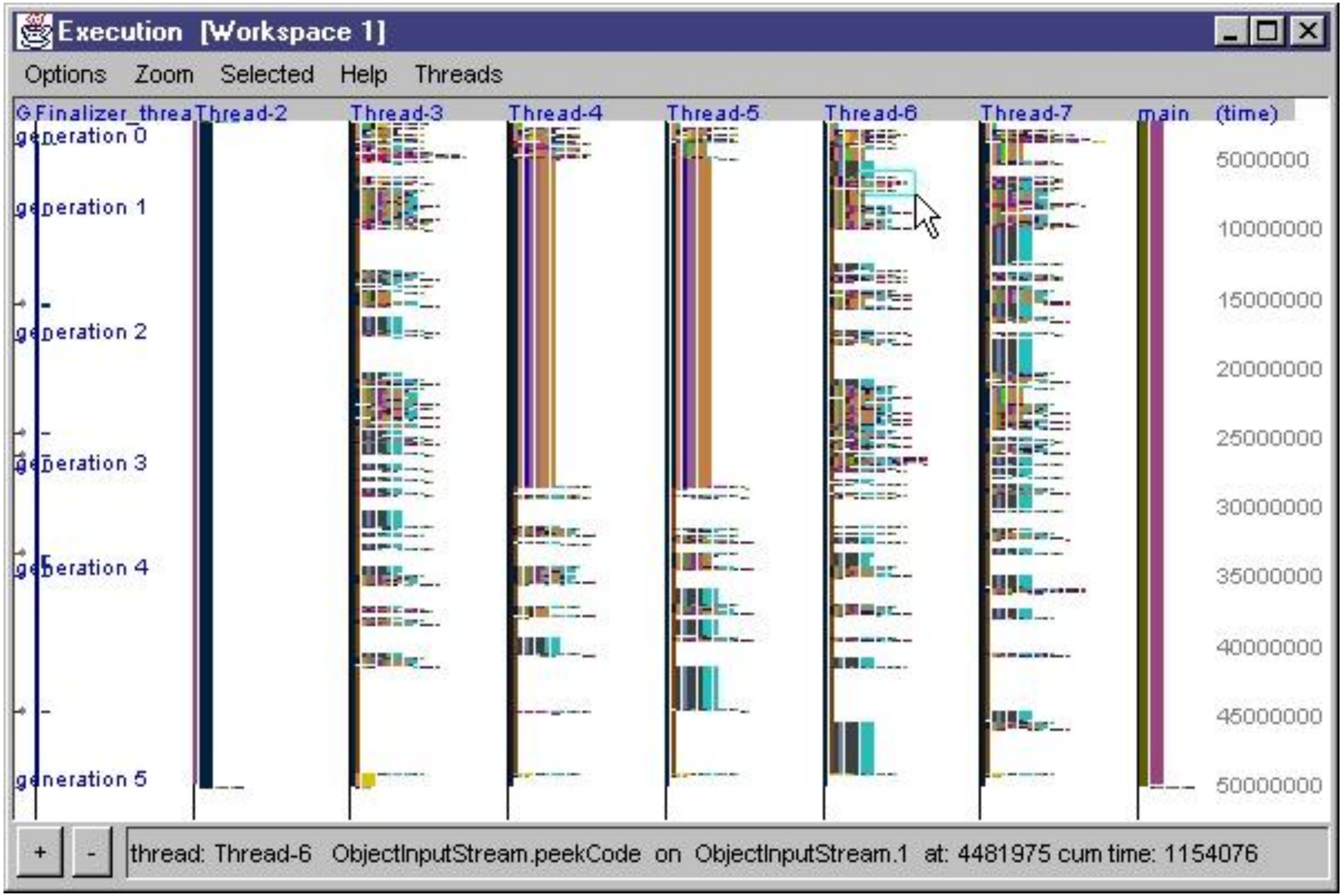
Call tree view:

Summarize call paths from or to a given set of method invocations

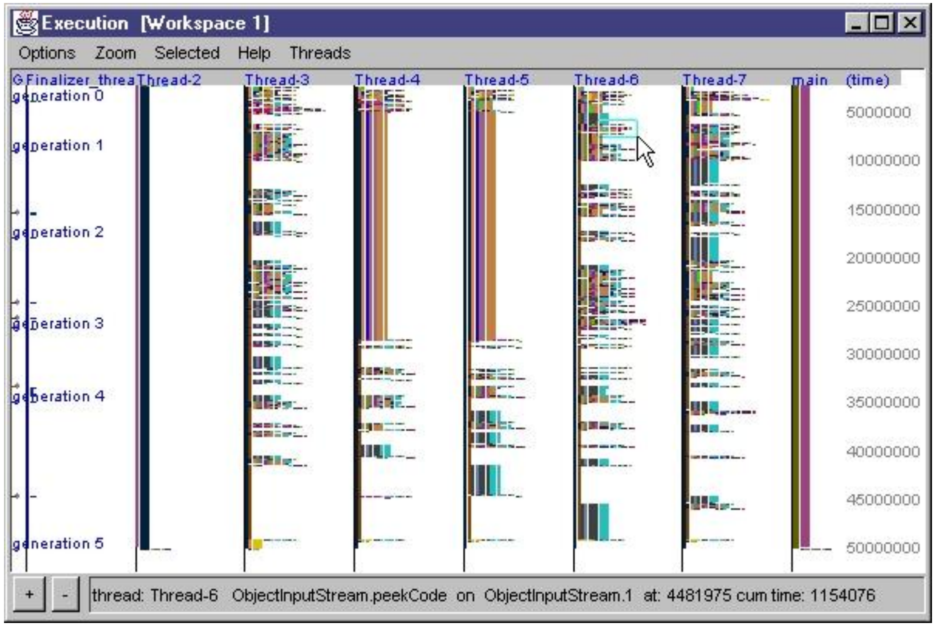


Execution view:

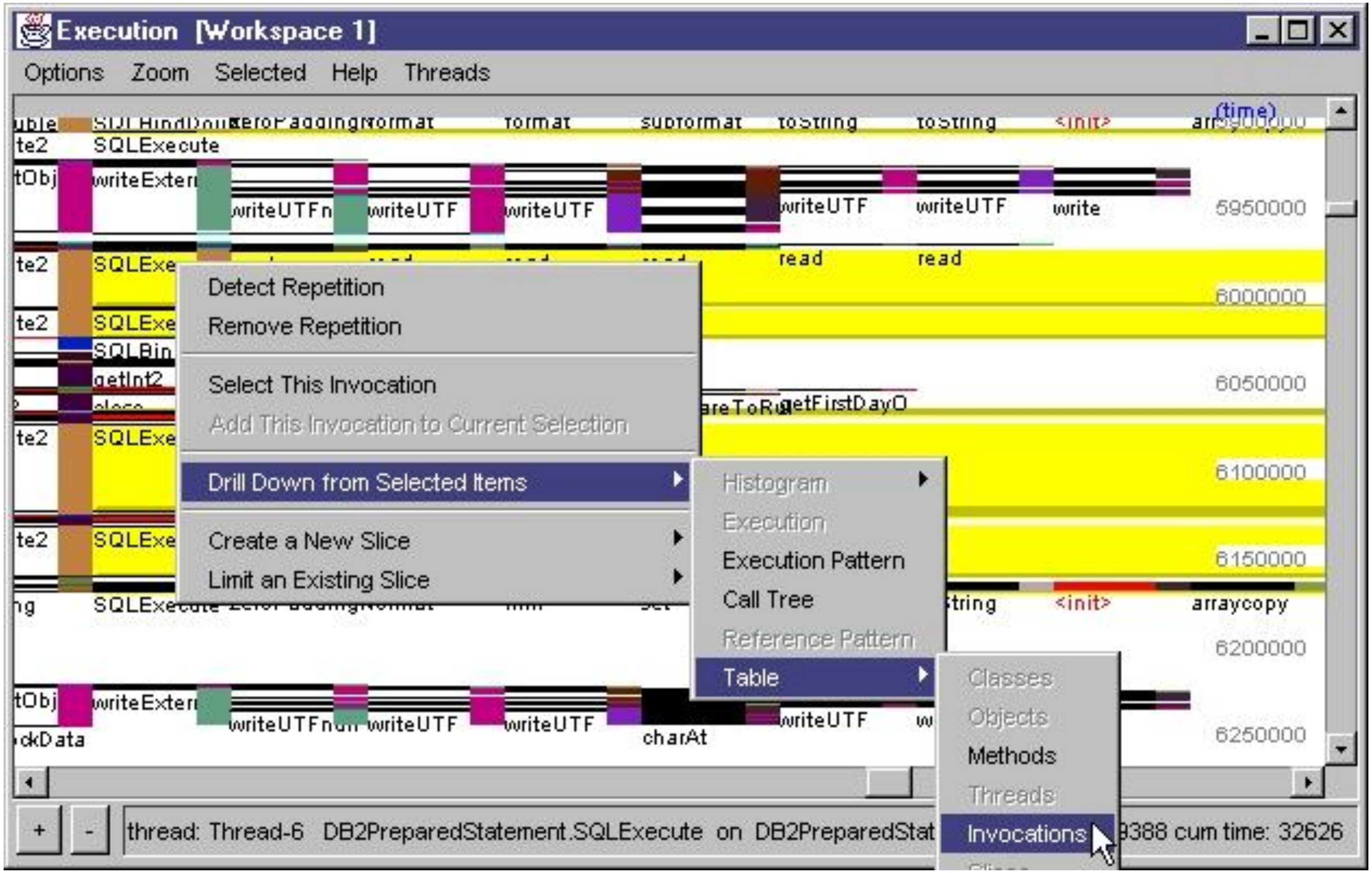
communication among objects per thread as a function of time



- Object represented by vertical stripe colored according to the object's class
- Time progresses downward and time units on right
- A stripe's top edge is the time of method call
  - The height reflects total time spent executing the method
- Stripes cascade to the right as methods sends messages
- Stripes grouped in columns by thread
- Leftmost column reserved for garbage collection information

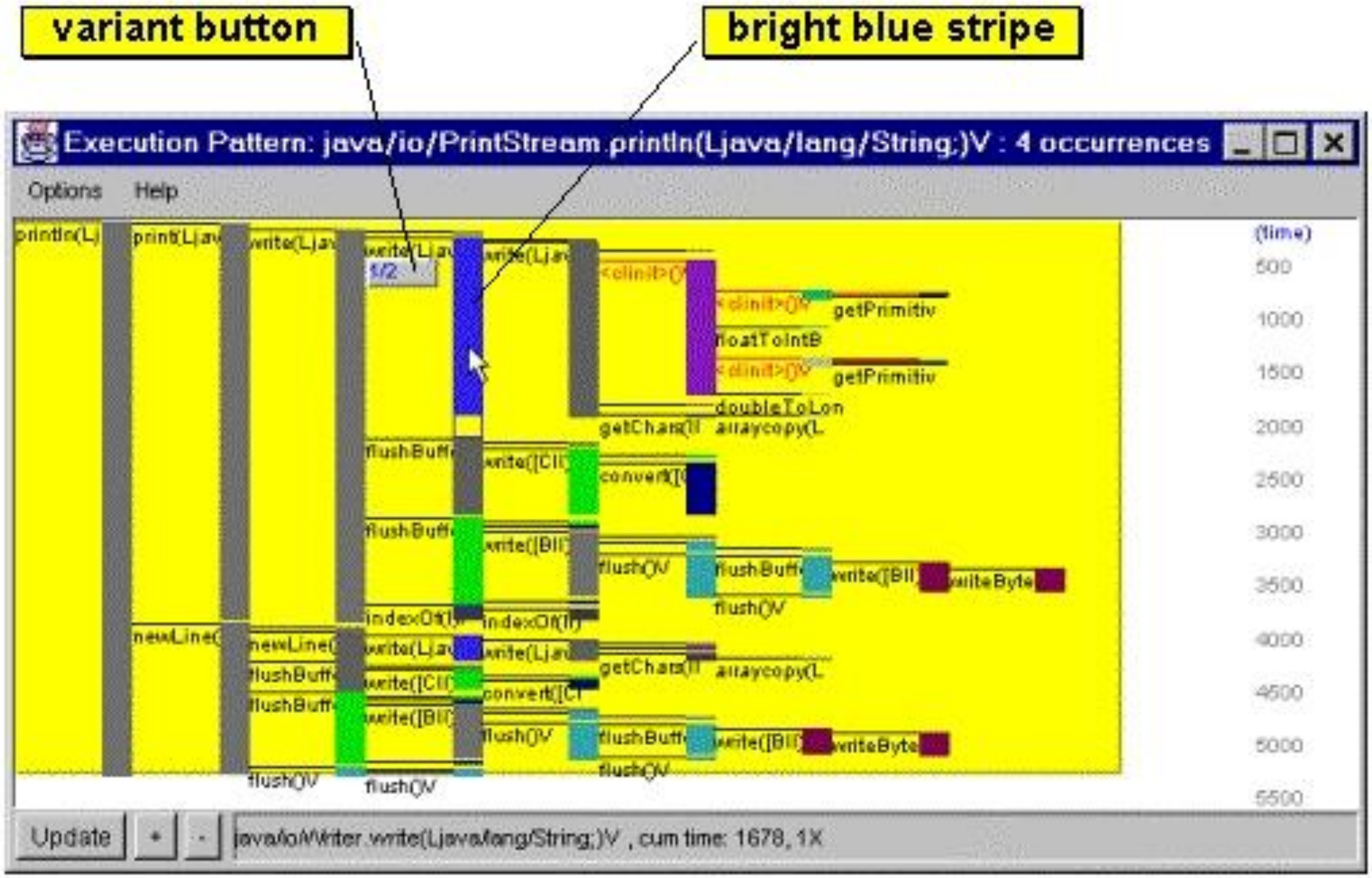


Zoomed in for detail



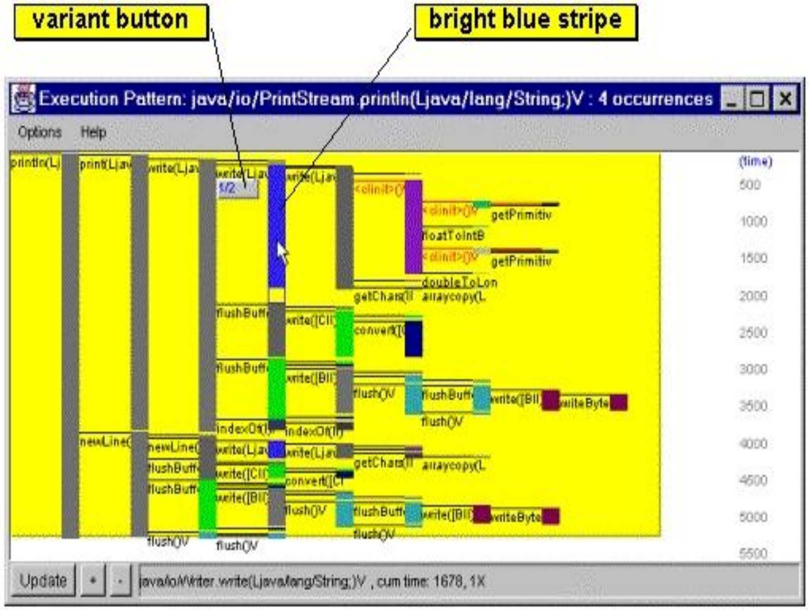
Execution pattern view: summarizes invocations of a method and highlights the differences

•

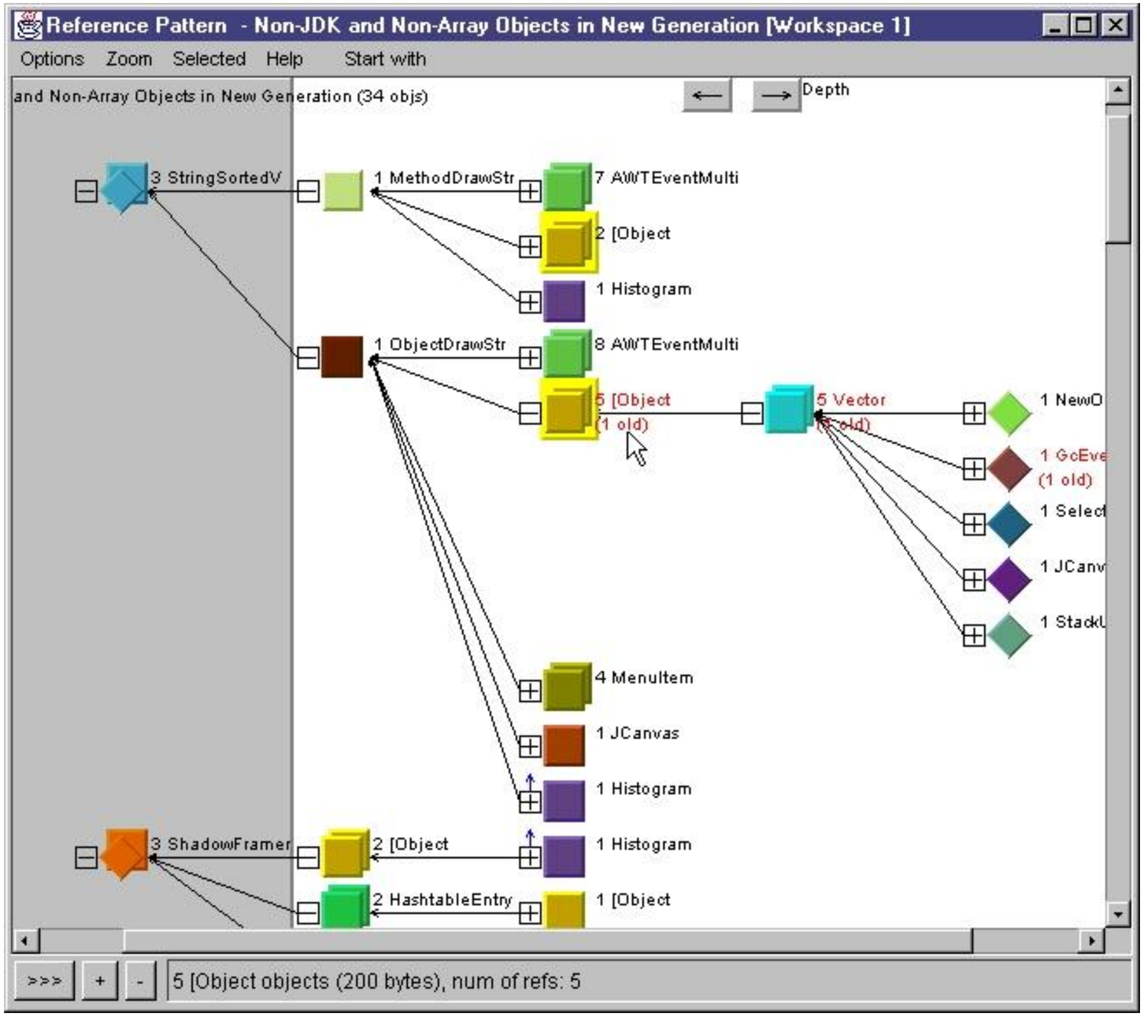


A summary of all the `println` occurrences in the trace

- Reveals that all `println` messages produce the same pattern of execution except for *one* area of divergence
- Mouse the bright blue stripe to identify it as a call to `java/io/Writer.write`.
  - "1X" indicates that this particular call pattern occurred just once
- ½ in beveled frame indicates there are two variant execution patterns at this point and that pattern 1 is shown

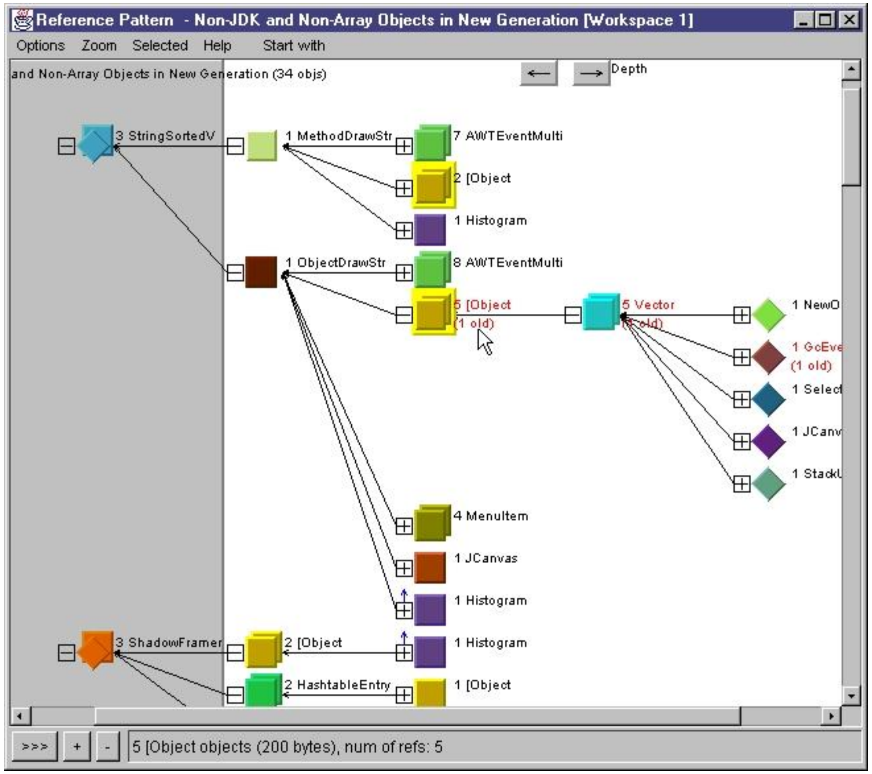


Reference pattern view



Shows patterns of references to or from a set of objects

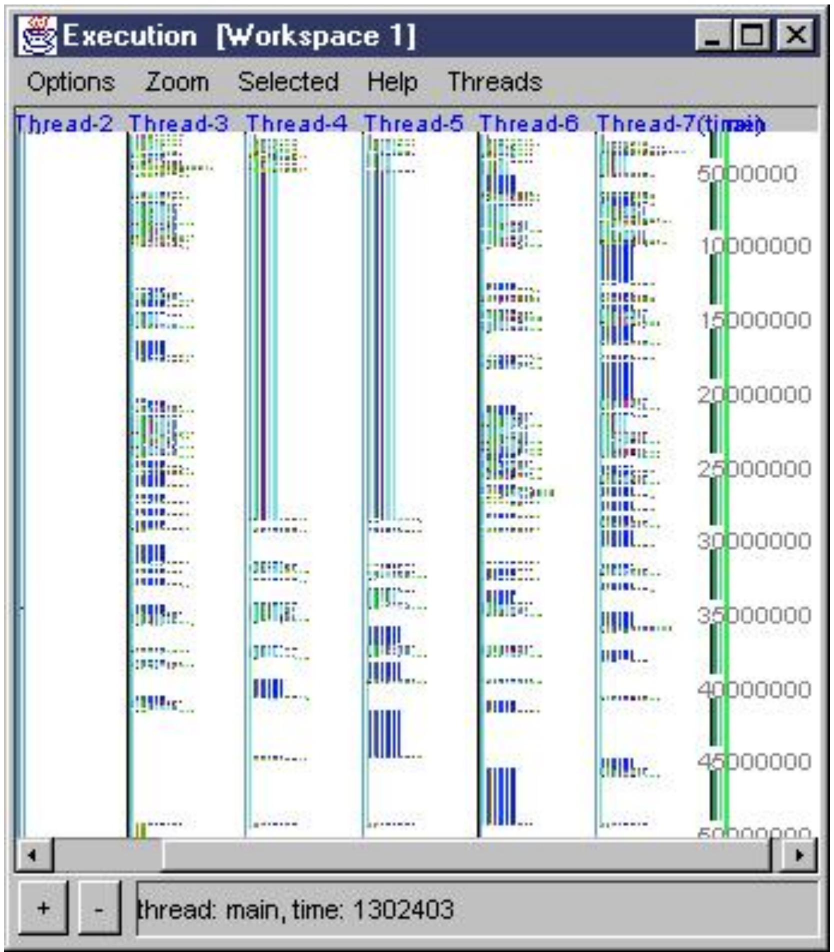
- Squares represent objects, each colored uniquely by class
- A diamond represents a class object
- Single squares denotes a single instance
- Twin squares represent multiple instances
- Arrows between nodes denote one or more references between instances
- An arrow points to the object(s) being referenced

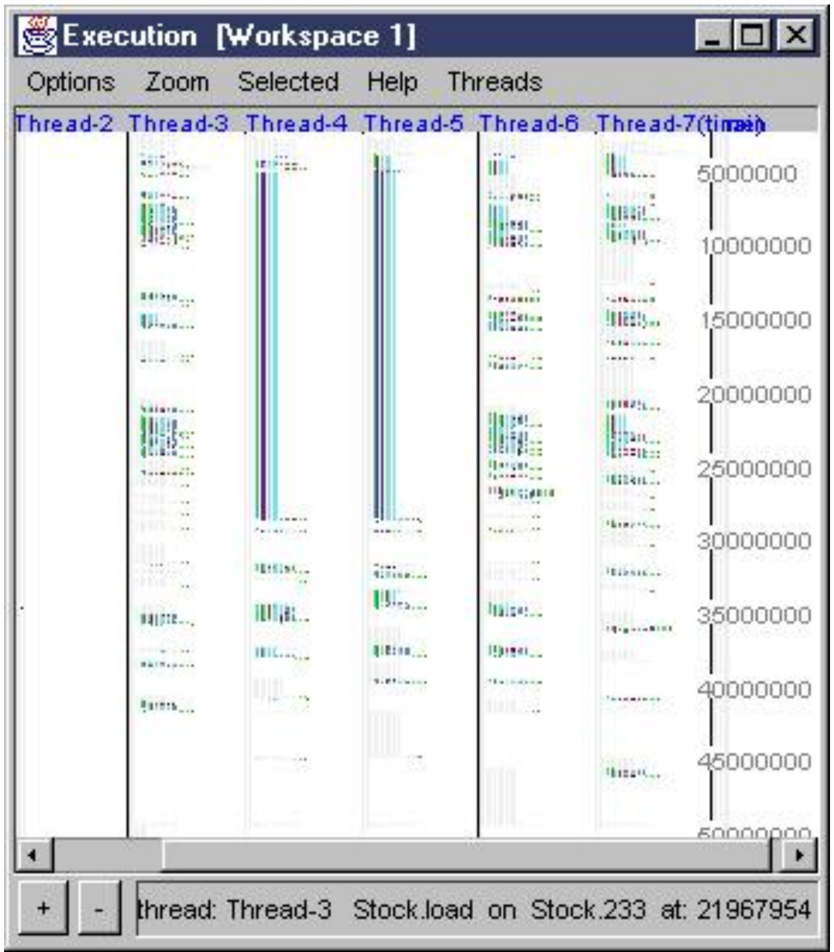


Slices
(not Weiser slices)

- A slice is a subset of the trace information corresponding to a user-selected feature in a program
  - Applies to any view
- Slices intended to filter out extraneous information, focusing analysis on one area
- Slices give you an extra dimension for measuring program execution
  - Can compute any measurement about a program relative to any defined slice
    - Ex: define slices to represent functional areas of your program; then measure execution time in each thread, method, method invocation, etc. spent in each functional area

Workspaces: collections of filterings





Happy Turkey!