PREfix

Optional reading: ***A Static Analyzer for Finding Dynamic Programming Errors***

15-413
Introduction to Software Engineering
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Find the Bugs!

```
char *f(int size) {
    char * result;
    if (size > 0)
        result = (char *)malloc(size);
    if (size == 1)
        return NULL;        // memory leak
    result[0] = 0;          // result may be uninitialized
                            // malloc may have failed
    return result;
}
```

Motivation

- Finding programming errors
  - invalid pointers
  - storage allocation errors
  - uninitialized memory
  - improper operations on resources

Can’t we just test?

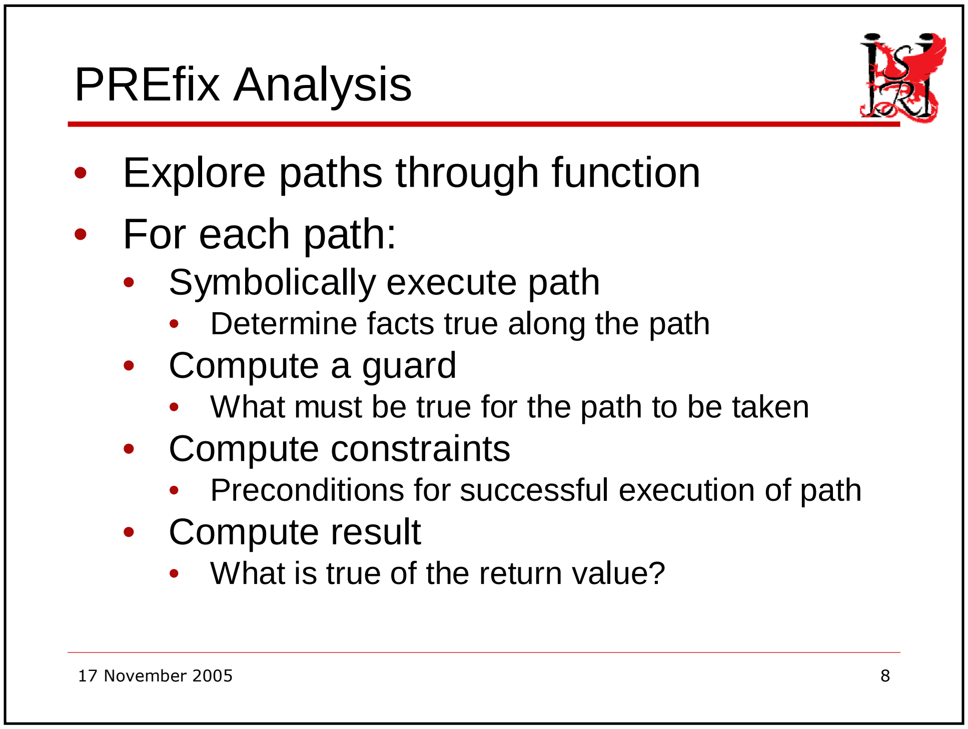
- 90% of errors involve interactions of multiple functions
  - Is this why the original developer didn’t find them?
- Occur in unusual or error conditions
  - Often hard to exercise with testing

Problems with Other Tools

- False Negatives
  - They look only in one function and miss errors
- False Positives
  - They report errors that can’t really occur
- Hard to use
  - Require extensive program annotations
- Require test cases
  - May be impractical
  - Only as good as your test suite

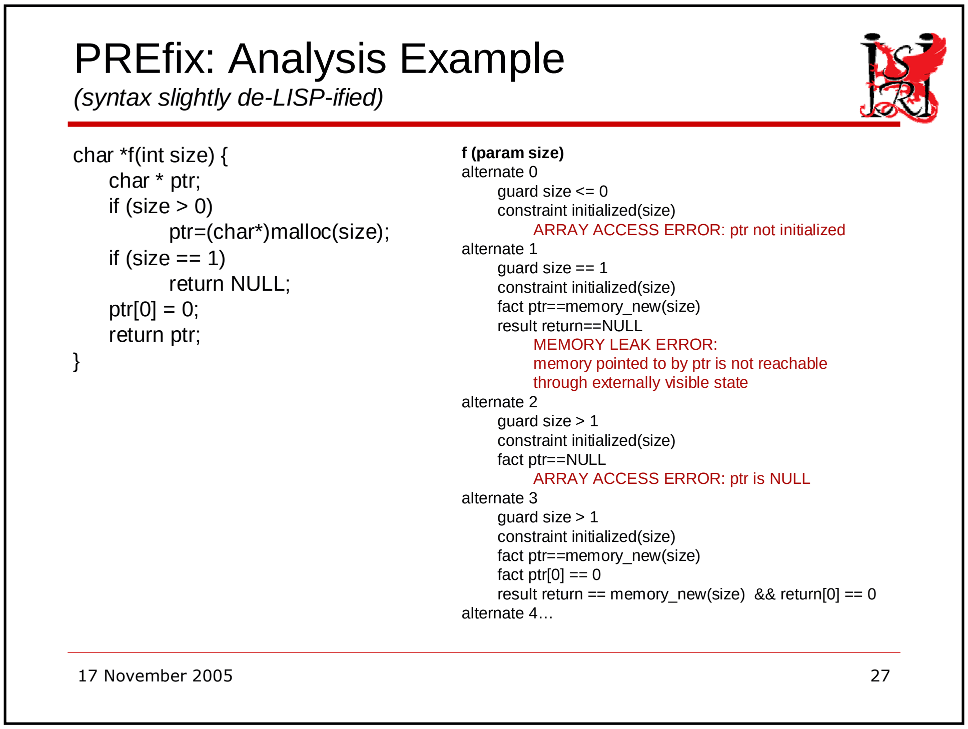
Goals of PREfix

- Handle hard aspects of C-like languages
  - Pointers, arrays, unions, libraries, casts…
- Don't require user annotations
  - Build on language semantics
- Avoid false positives
  - Use path-sensitive analysis
- Give the user good feedback
  - Why might an error occur? Show the user an example execution



PREfix Analysis

- Explore paths through function
- For each path:
  - Symbolically execute path
    - Determine facts true along the path
  - Compute a guard
    - What must be true for the path to be taken
  - Compute constraints
    - Preconditions for successful execution of path
  - Compute result
    - What is true of the return value?

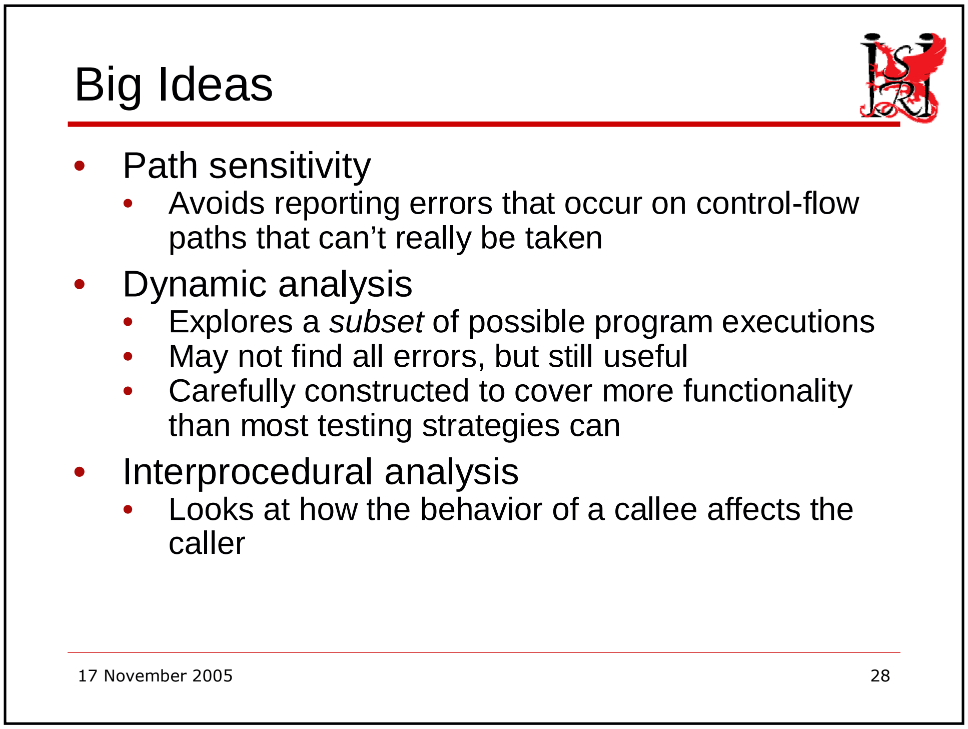


PREfix: Analysis Example

(syntax slightly de-LISP-ified)

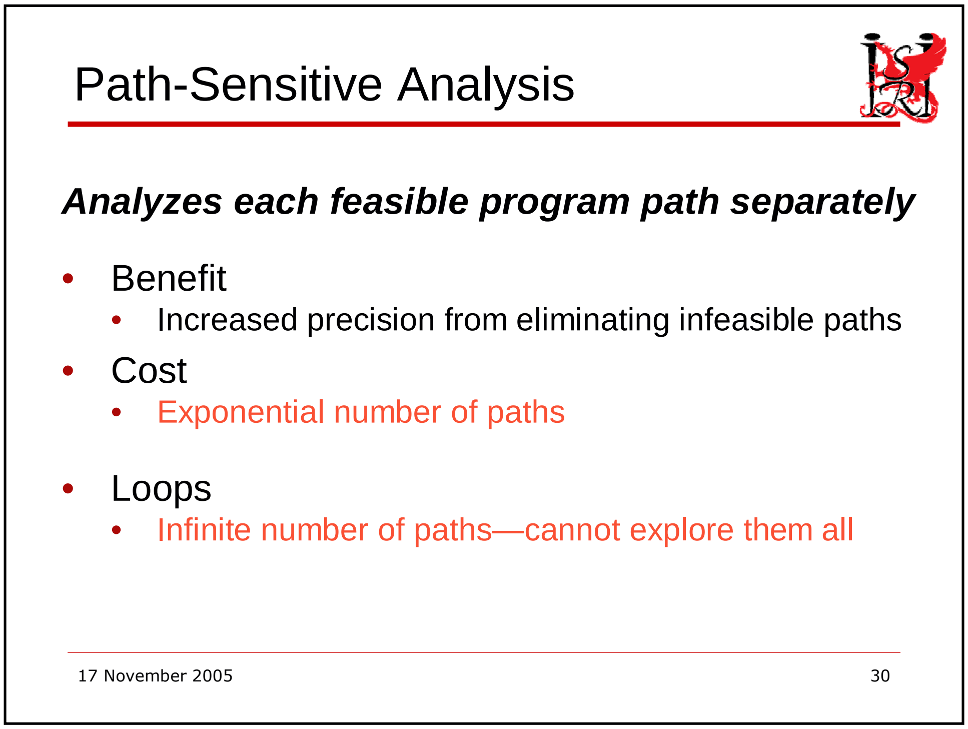
```
char *f(int size) {
    char * ptr;
    if (size > 0)
            ptr=(char*)malloc(size);
    if (size == 1)
            return NULL;
    ptr[0] = 0;
    return ptr;
}
```

```
f (param size)
alternate 0
    guard size <= 0
    constraint initialized(size)
        ARRAY ACCESS ERROR: ptr not initialized
alternate 1
    guard size == 1
    constraint initialized(size)
    fact ptr==memory_new(size)
    result return==NULL
        MEMORY LEAK ERROR:
        memory pointed to by ptr is not reachable
        through externally visible state
alternate 2
    guard size > 1
    constraint initialized(size)
    fact ptr==NULL
        ARRAY ACCESS ERROR: ptr is NULL
alternate 3
    guard size > 1
    constraint initialized(size)
    fact ptr==memory_new(size)
    fact ptr[0] == 0
    result return == memory_new(size)  && return[0] == 0
alternate 4…
```



Big Ideas

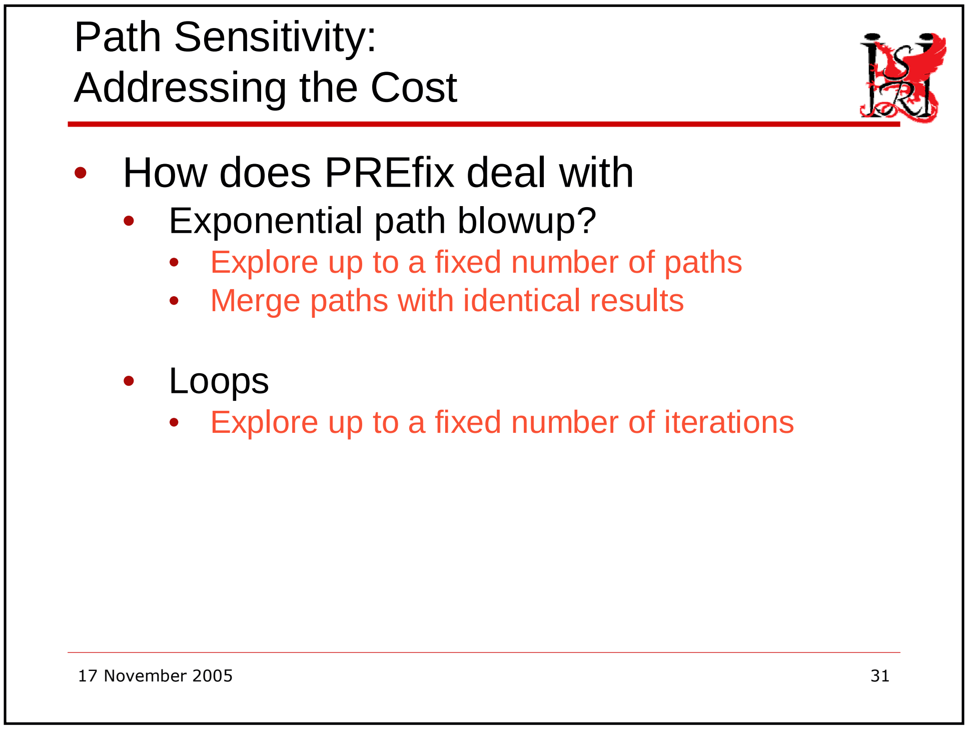
- Path sensitivity
  - Avoids reporting errors that occur on control-flow paths that can’t really be taken
- Dynamic analysis
  - Explores a *subset* of possible program executions
  - May not find all errors, but still useful
  - Carefully constructed to cover more functionality than most testing strategies can
- Interprocedural analysis
  - Looks at how the behavior of a callee affects the caller



Path-Sensitive Analysis

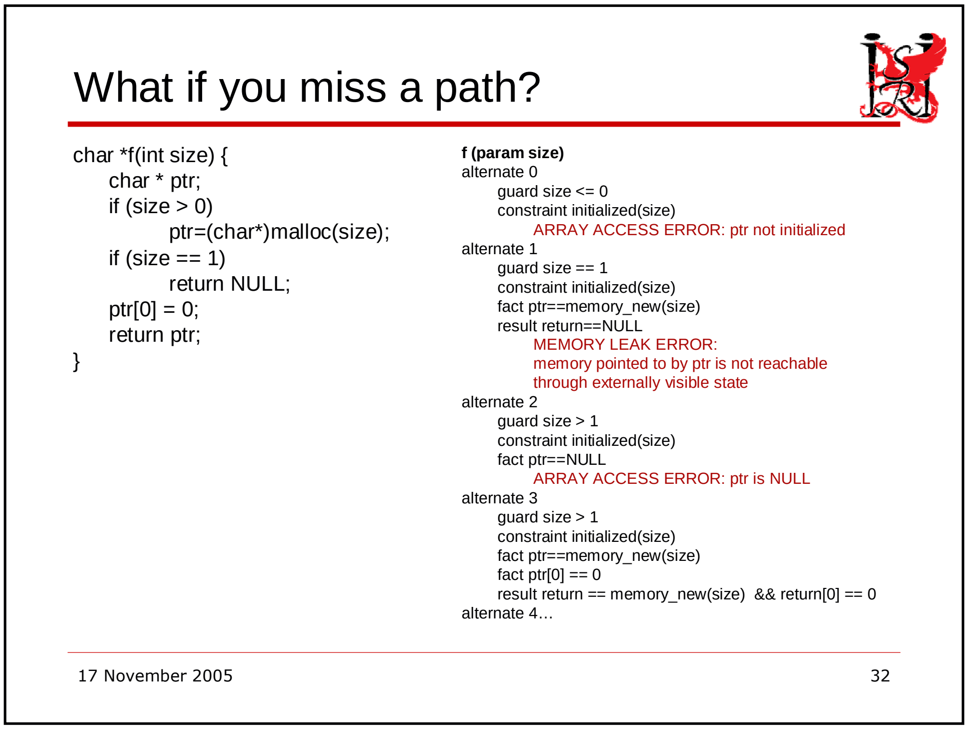
Analyzes each feasible program path separately

- Benefit
  - Increased precision from eliminating infeasible paths
- Cost
  - Exponential number of paths
- Loops
  - Infinite number of paths—cannot explore them all



Path Sensitivity: Addressing the Cost

- How does PREfix deal with
  - Exponential path blowup?
    - Explore up to a fixed number of paths
    - Merge paths with identical results
  - Loops
    - Explore up to a fixed number of iterations



What if you miss a path?

```
char *f(int size) {
      char * ptr;
      if (size > 0)
                ptr=(char*)malloc(size);
      if (size == 1)
                return NULL;
      ptr[0] = 0;
      return ptr;
}
```

```
f (param size)
alternate 0
      guard size <= 0
      constraint initialized(size)
            ARRAY ACCESS ERROR: ptr not initialized
alternate 1
      guard size == 1
      constraint initialized(size)
      fact ptr==memory_new(size)
      result return==NULL
            MEMORY LEAK ERROR:
            memory pointed to by ptr is not reachable
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alternate 2
      guard size > 1
      constraint initialized(size)
      fact ptr==NULL
            ARRAY ACCESS ERROR: ptr is NULL
alternate 3
      guard size > 1
      constraint initialized(size)
      fact ptr==memory_new(size)
      fact ptr[0] == 0
      result return == memory_new(size)  && return[0] == 0
alternate 4…
```
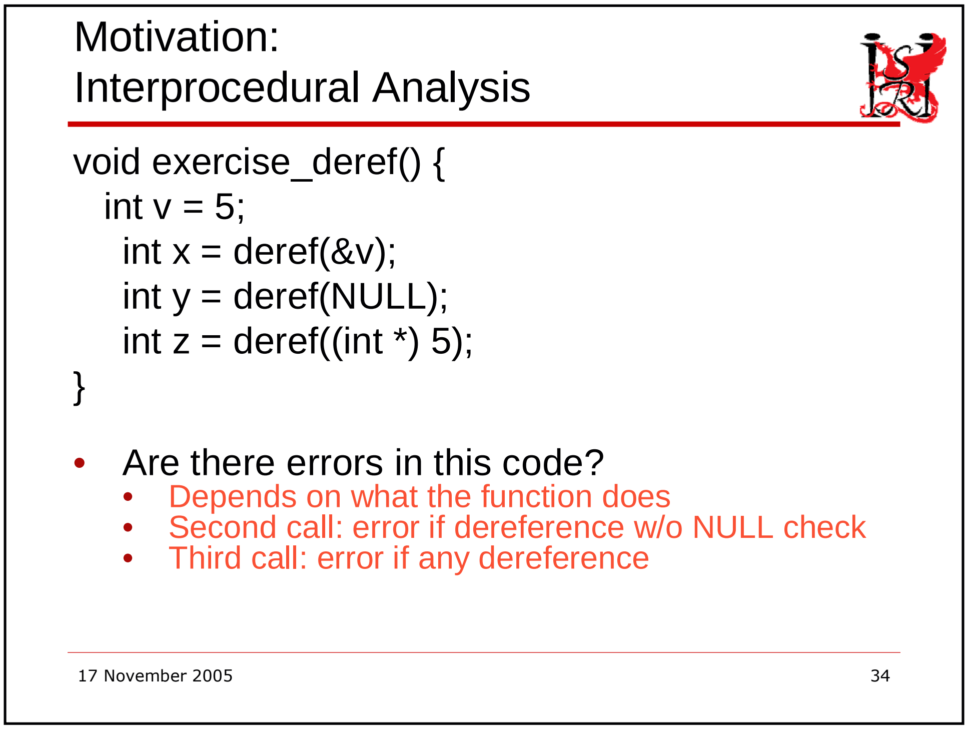
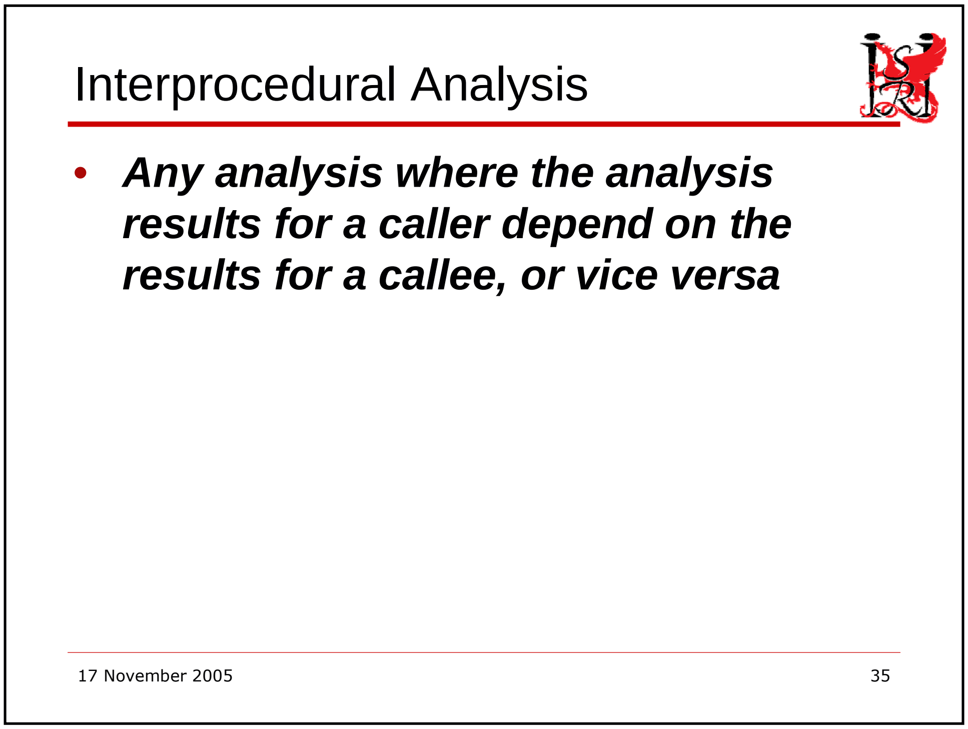



Motivation: Interprocedural Analysis

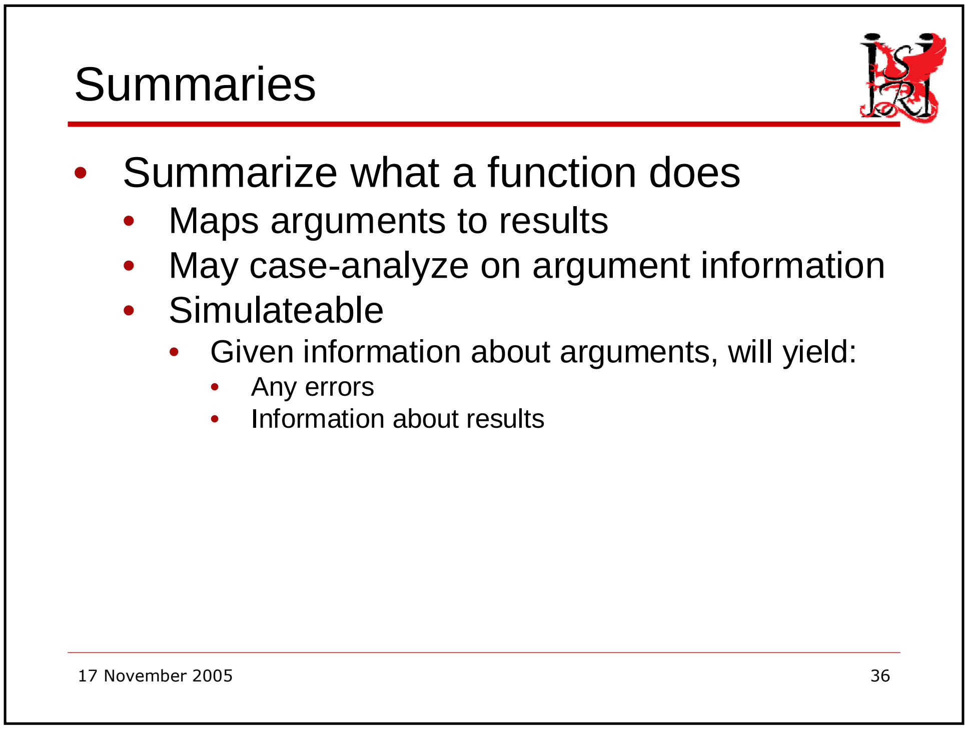
```
void exercise_deref() {
  int v = 5;
    int x = deref(&v);
    int y = deref(NULL);
    int z = deref((int *) 5);
}
```

- Are there errors in this code?
  - Depends on what the function does
  - Second call: error if dereference w/o NULL check
  - Third call: error if any dereference



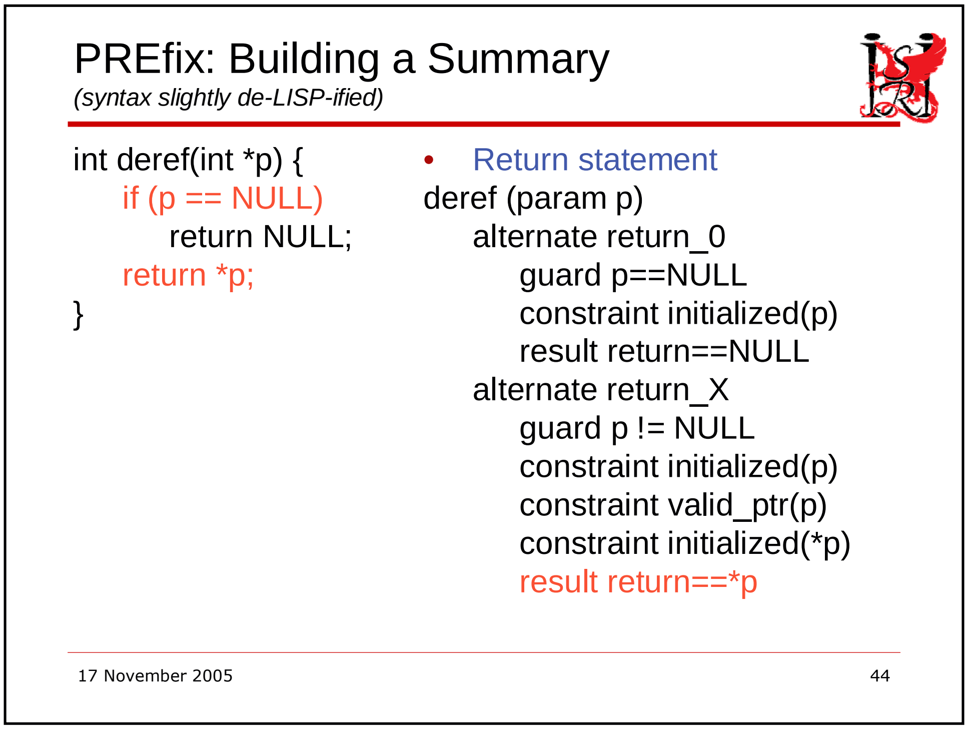
Interprocedural Analysis

- ***Any analysis where the analysis results for a caller depend on the results for a callee, or vice versa***



Summaries

- Summarize what a function does
  - Maps arguments to results
  - May case-analyze on argument information
  - Simulateable
    - Given information about arguments, will yield:
      - Any errors
      - Information about results



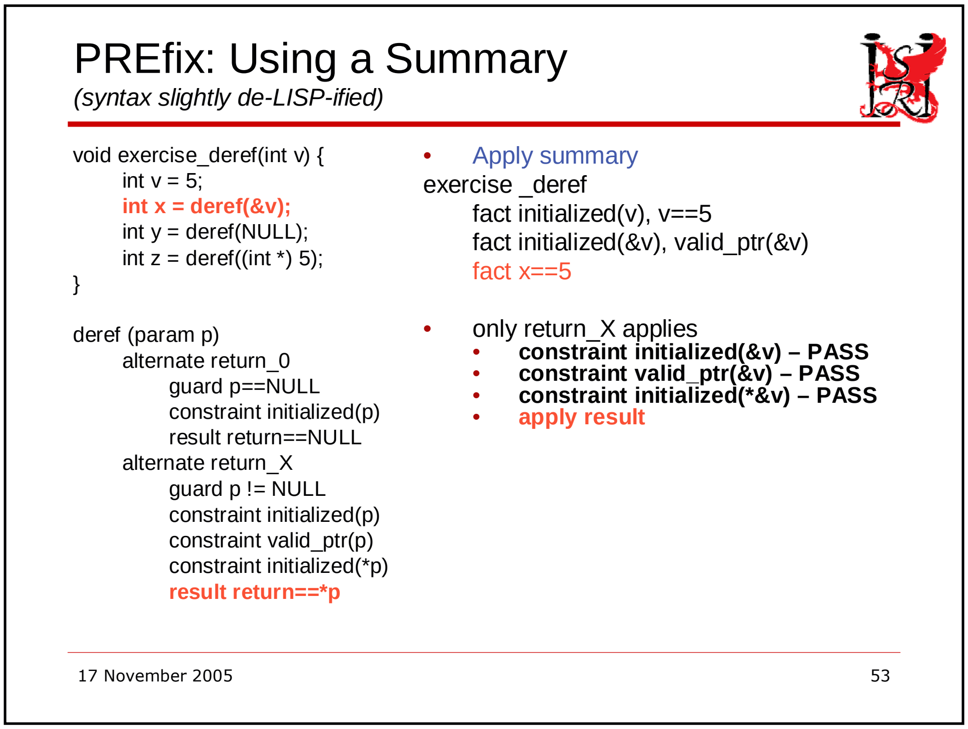
PREfix: Building a Summary

(syntax slightly de-LISP-ified)

```
int deref(int *p) {
    if (p == NULL)
        return NULL;
    return *p;
}
```

- Return statement

```
deref (param p)
    alternate return_0
        guard p==NULL
        constraint initialized(p)
        result return==NULL
    alternate return_X
        guard p != NULL
        constraint initialized(p)
        constraint valid_ptr(p)
        constraint initialized(*p)
        result return==*p
```



PREfix: Using a Summary

(syntax slightly de-LISP-ified)

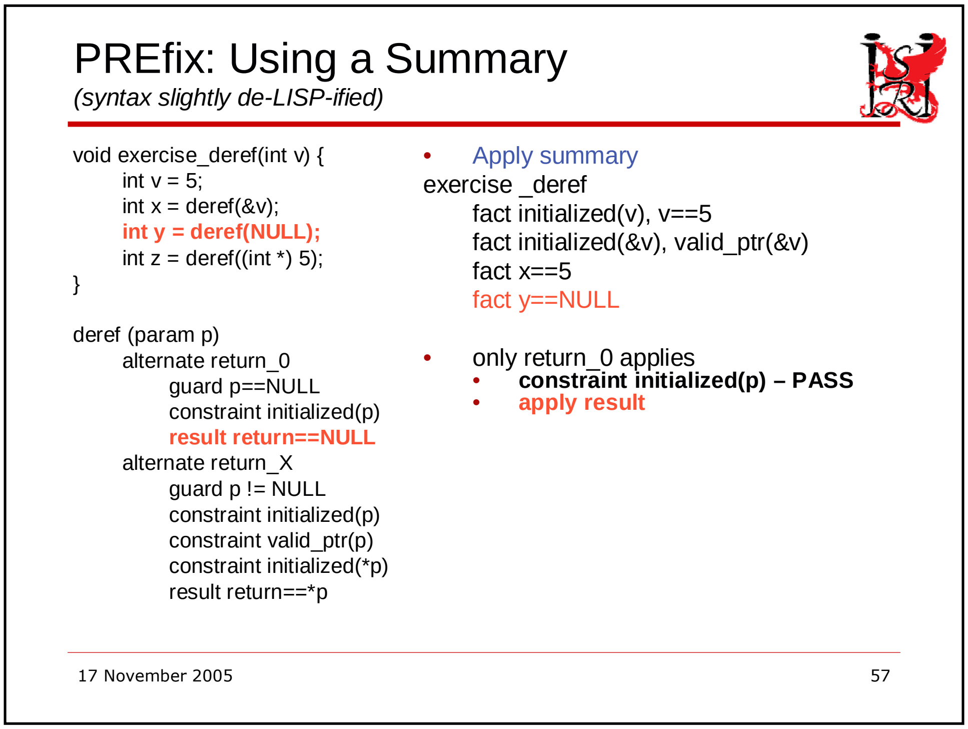
```
void exercise_deref(int v) {
      int v = 5;
      int x = deref(&v);
      int y = deref(NULL);
      int z = deref((int *) 5);
}

deref (param p)
      alternate return_0
            guard p==NULL
            constraint initialized(p)
            result return==NULL
      alternate return_X
            guard p != NULL
            constraint initialized(p)
            constraint valid_ptr(p)
            constraint initialized(*p)
            result return==*p
```

- Apply summary

exercise _deref

    fact initialized(v), v==5
    fact initialized(&v), valid_ptr(&v)
    fact x==5

- only return_X applies
  - **constraint initialized(&v) – PASS**
  - **constraint valid_ptr(&v) – PASS**
  - **constraint initialized(*&v) – PASS**
  - **apply result**



PREfix: Using a Summary

(syntax slightly de-LISP-ified)

```
void exercise_deref(int v) {
      int v = 5;
      int x = deref(&v);
      int y = deref(NULL);
      int z = deref((int *) 5);
}

deref (param p)
      alternate return_0
            guard p==NULL
            constraint initialized(p)
            result return==NULL
      alternate return_X
            guard p != NULL
            constraint initialized(p)
            constraint valid_ptr(p)
            constraint initialized(*p)
            result return==*p
```

- Apply summary

exercise _deref

    fact initialized(v), v==5
    fact initialized(&v), valid_ptr(&v)
    fact x==5
    fact y==NULL

- only return_0 applies
  - **constraint initialized(p) – PASS**
  - **apply result**

PREfix: Using a Summary

(syntax slightly de-LISP-ified)

```
void exercise_deref(int v) {
        int v = 5;
        int x = deref(&v);
        int y = deref(NULL);
        int z = deref((int *) 5);
}

deref (param p)
        alternate return_0
                guard p==NULL
                constraint initialized(p)
                result return==NULL
        alternate return_X
                guard p != NULL
                constraint initialized(p)
                constraint valid_ptr(p)
                constraint initialized(*p)
                result return==*p
```

- Apply summary

exercise _deref

fact initialized(v), v==5

fact initialized(&v), valid_ptr(&v)

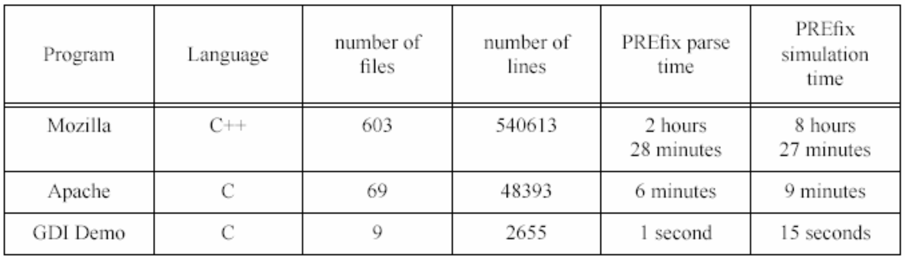
fact x==5

fact y==NULL

fact !valid_ptr((int *) 5), (int *) 5 != NULL

- return_0 does not apply
- return_X does apply
  - constraint initialized((int *) 5) – PASS
  - **constraint valid_ptr((int *) 5) – FAIL**
    - **Generate error**

PREfix Scaleability

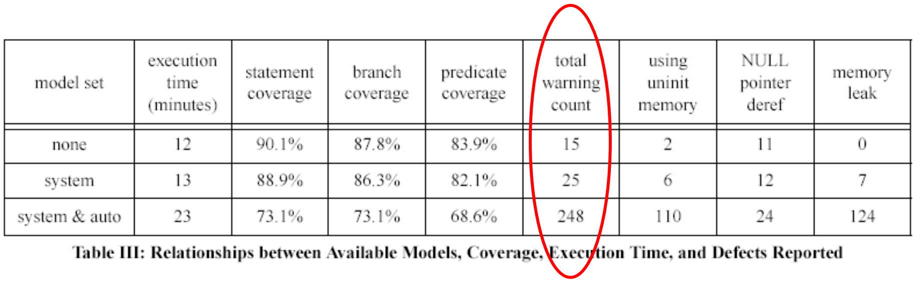


Program	Language	number of files	number of lines	PREfix parse time	PREfix simulation time
Mozilla	C++	603	540613	2 hours 28 minutes	8 hours 27 minutes
Apache	C	69	48393	6 minutes	9 minutes
GDI Demo	C	9	2655	1 second	15 seconds

Table I: Performance on Sample Public Domain Software

- Analysis cost = 2x-5x build cost
  - Scales linearly
    - Probably due to fixed cutoff on number of paths

Value of Interprocedural Analysis

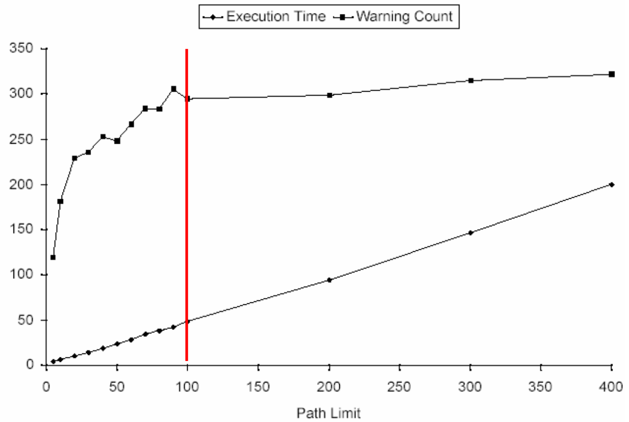


model set	execution time (minutes)	statement coverage	branch coverage	predicate coverage	total warning count	using uninit memory	NULL pointer deref	memory leak
none	12	90.1%	87.8%	83.9%	15	2	11	0
system	13	88.9%	86.3%	82.1%	25	6	12	7
system & auto	23	73.1%	73.1%	68.6%	248	110	24	124

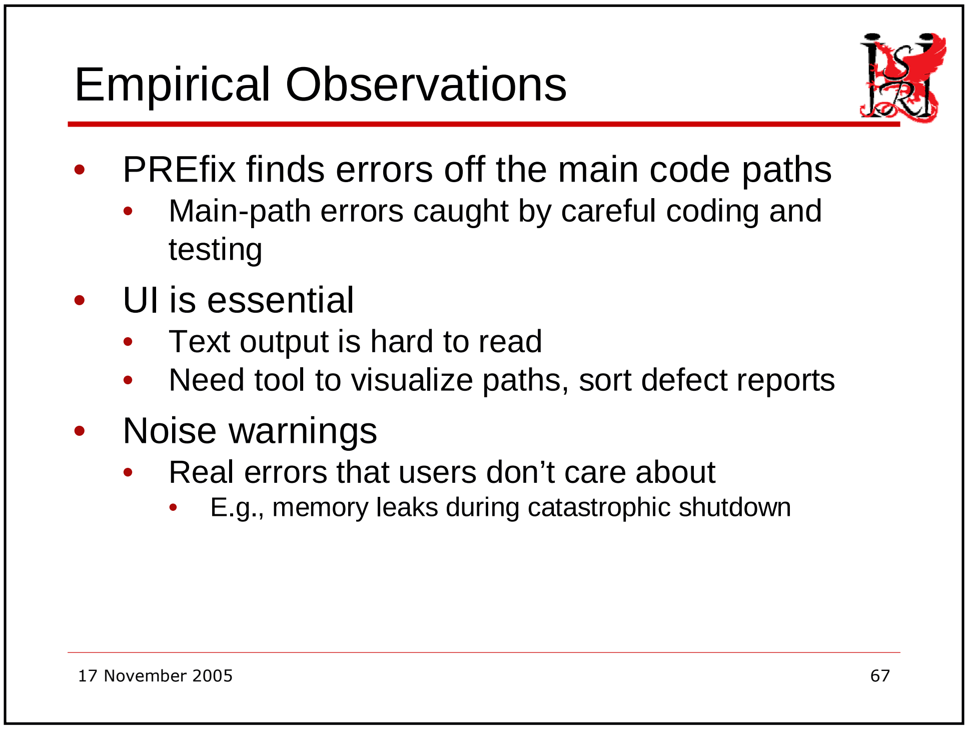
Table III: Relationships between Available Models, Coverage, Execution Time, and Defects Reported

- 90% of errors require models (summaries)

You don’t need every path

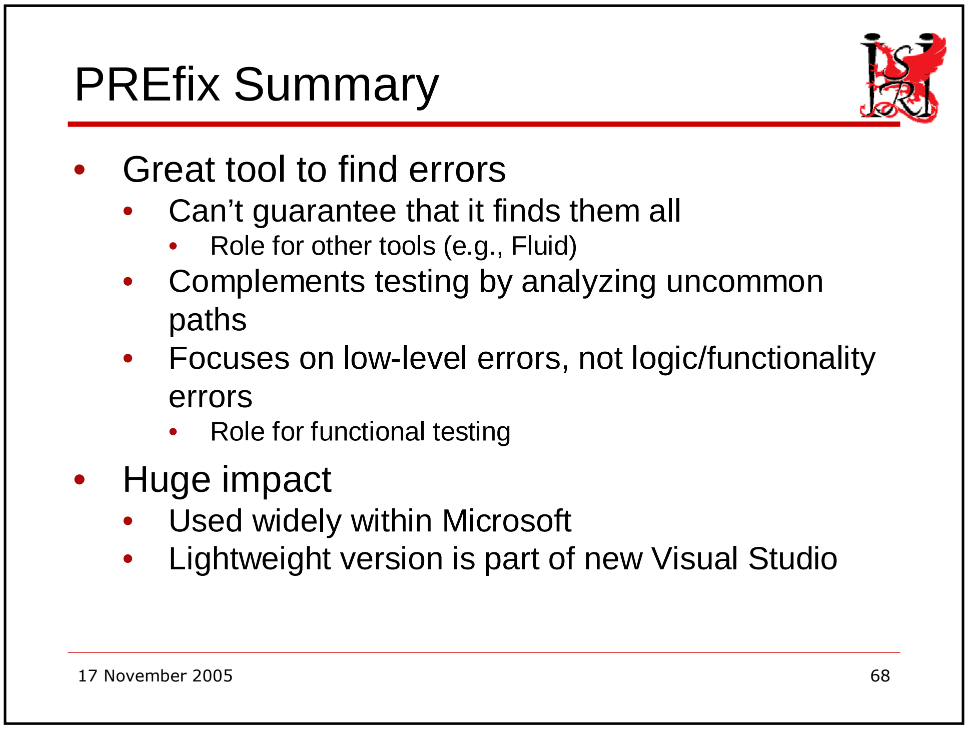


- Get most of the warnings with 100 paths



Empirical Observations

- PREfix finds errors off the main code paths
  - Main-path errors caught by careful coding and testing
- UI is essential
  - Text output is hard to read
  - Need tool to visualize paths, sort defect reports
- Noise warnings
  - Real errors that users don't care about
    - E.g., memory leaks during catastrophic shutdown



PREfix Summary

- Great tool to find errors
  - Can't guarantee that it finds them all
    - Role for other tools (e.g., Fluid)
  - Complements testing by analyzing uncommon paths
  - Focuses on low-level errors, not logic/functionality errors
    - Role for functional testing
- Huge impact
  - Used widely within Microsoft
  - Lightweight version is part of new Visual Studio