Buffer Overrun Detection using Linear Programming and Static Analysis

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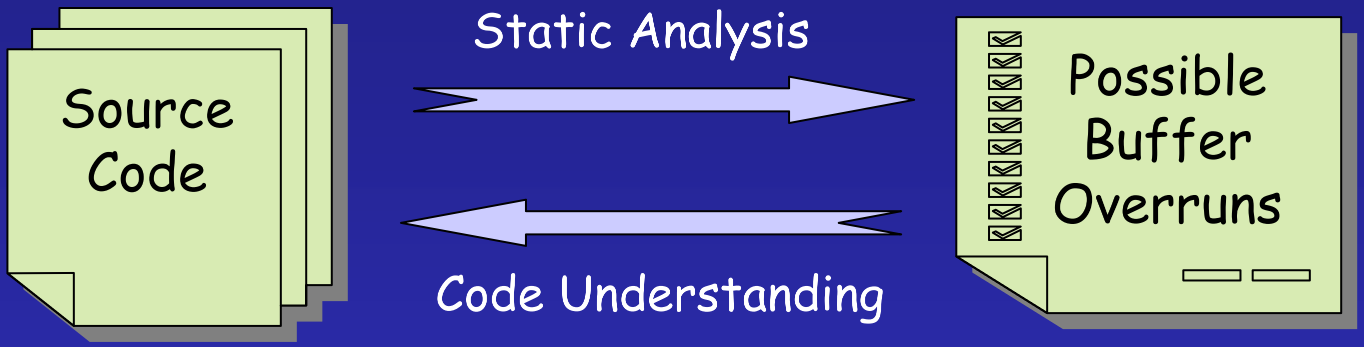
The Problem: Buffer Overflows

- Highly exploited class of vulnerabilities
  - Legacy programs in C are still vulnerable
  - "Safe" functions can be used unsafely

- Need:
  - Automatic techniques that will assure code is safe before it is deployed

The Solution



- Use static program analysis
- Produce a list of possibly vulnerable program locations
- Couple buffer overrun warnings with code understanding techniques

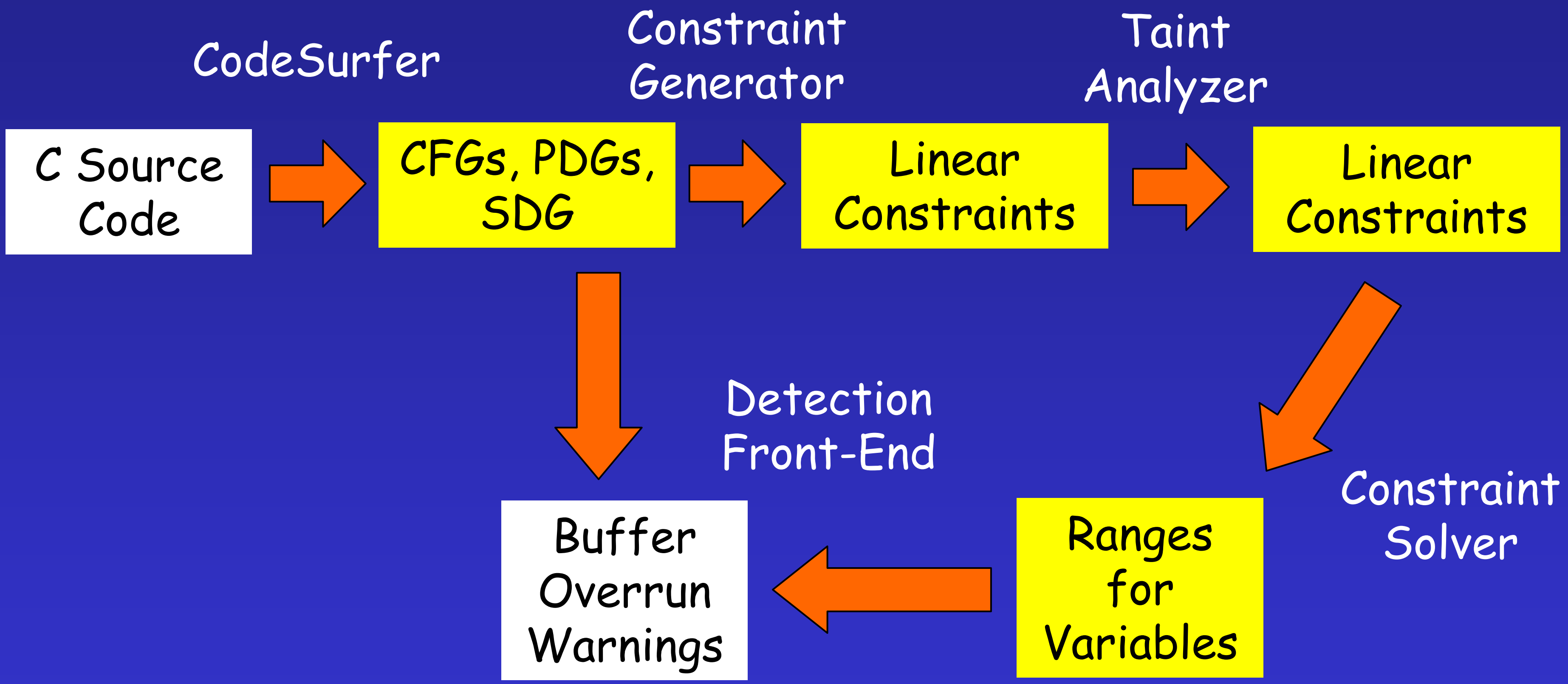
Our Contributions

- Program Analysis:
  - Incorporated buffer overrun detection in a program understanding tool
    - Program slicing, Data predecessors,…
  - Use of procedure summaries to make buffer overrun analysis context-sensitive
- Constraint Resolution:
  - Use of linear programming to solve a range analysis problem

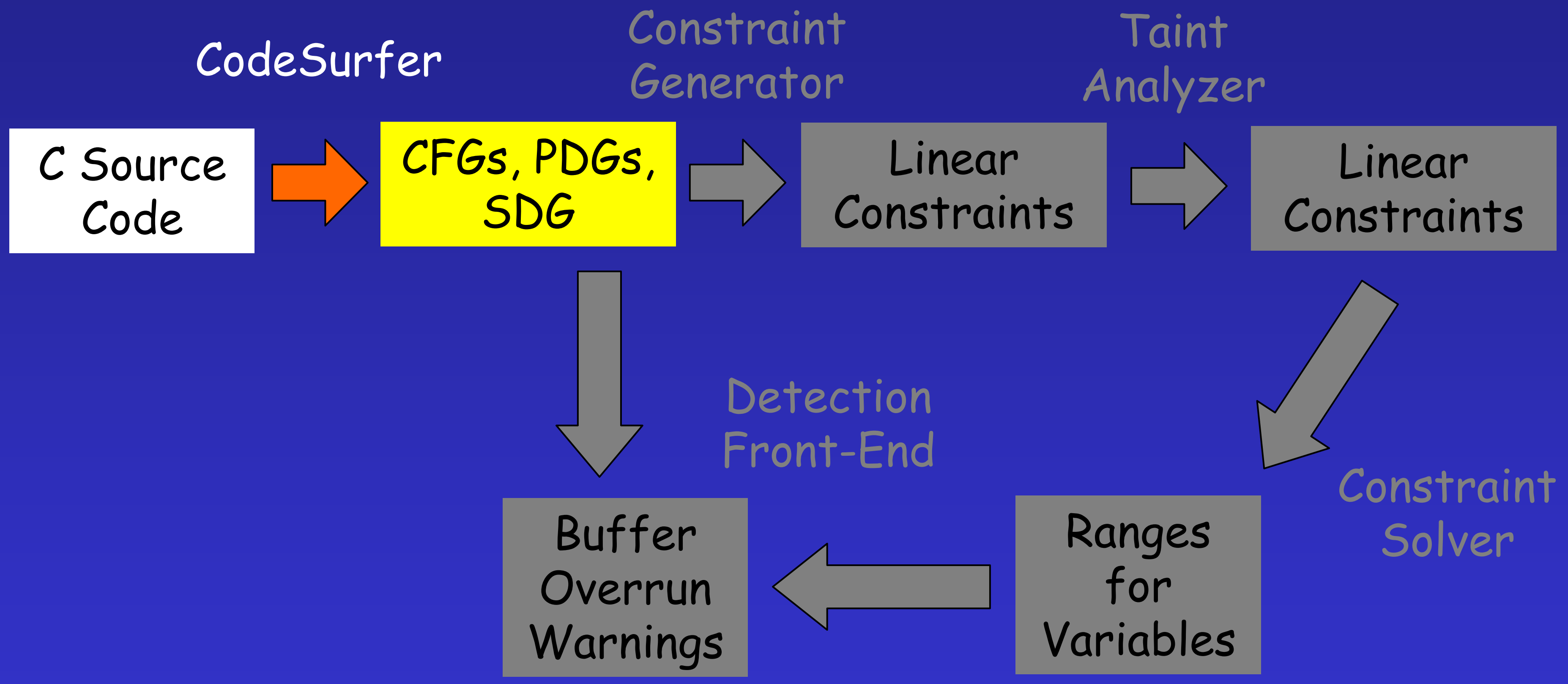
Roadmap of Talk

- Tool Architecture
  - Constraint Generation
  - Constraint Resolution
  - Producing Warnings
- Adding Context Sensitivity
- Results
- Future work and Conclusions

Tool Architecture



CodeSurfer


CodeSurfer
C Source Code
CFGs, PDGs, SDG
Constraint Generator
Linear Constraints
Taint Analyzer
Linear Constraints
Constraint Solver
Ranges for Variables
Detection Front-End
Buffer Overrun Warnings

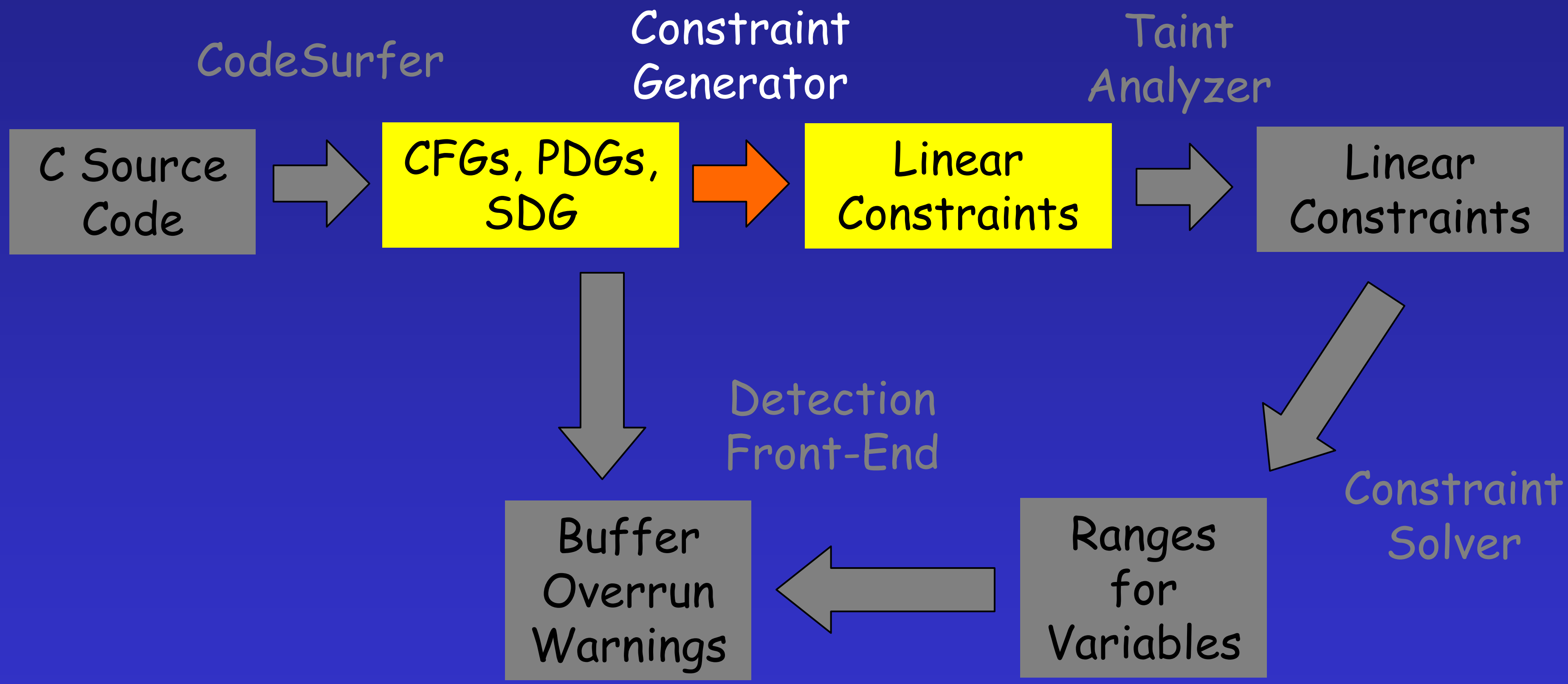
CodeSurfer

- Commercial tool from Grammatech Inc.
- Code understanding framework
  - Inter-procedural slicing, chopping…
- Internally constructs:
  - Control Flow Graph (CFG)
  - Program Dependence Graphs (PDG)
  - System Dependence Graph (SDG)
- Incorporates results of pointer analysis
  - Helps reduce the number of warnings

The Role of CodeSurfer

- Program Analysis Framework:
  - Use internal data structures to generate constraints
- Detection Front-end:
  - Link each warning to corresponding lines of source code through the System Dependence Graph
  - Interactive front-end

Constraint Generation



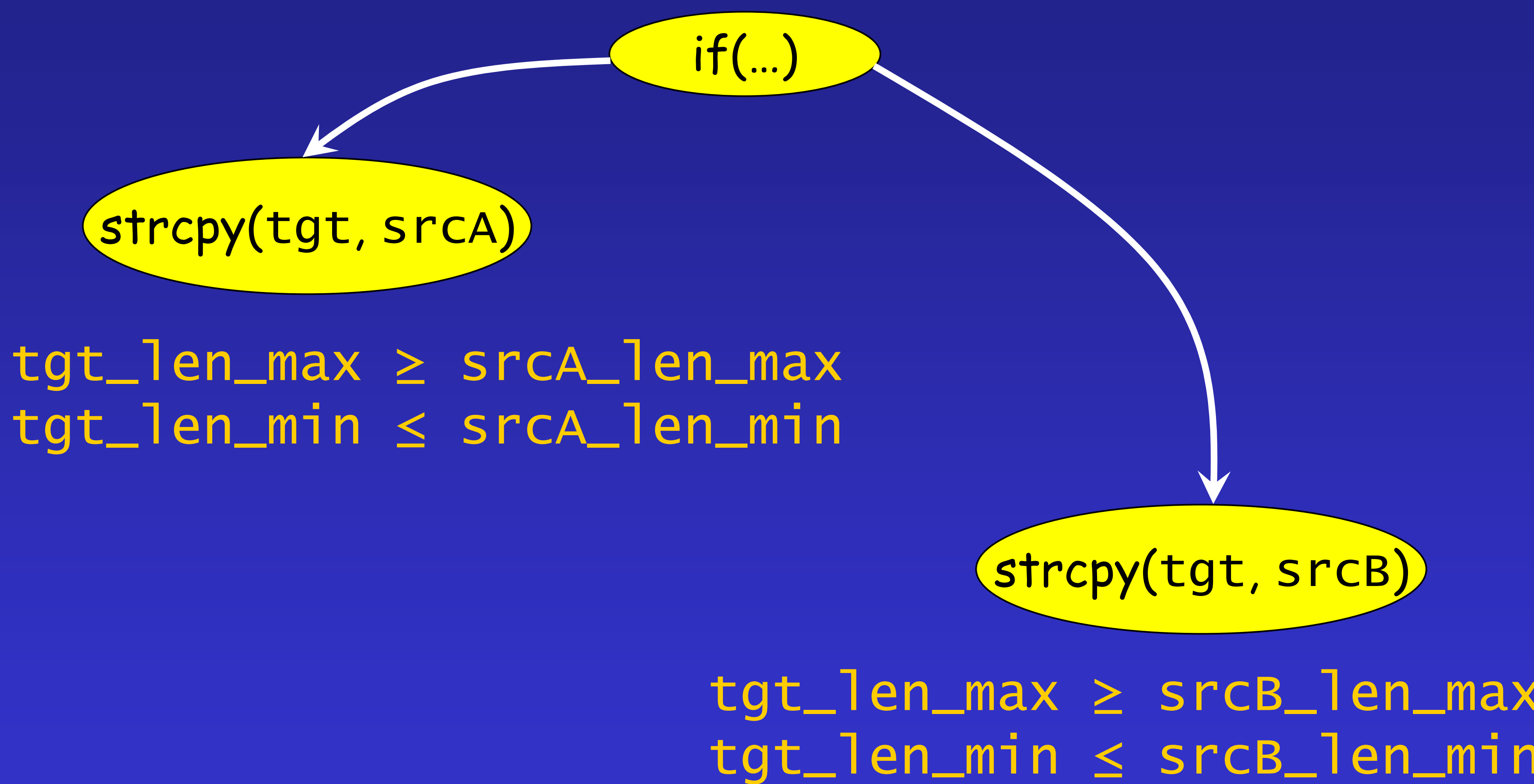
Constraint Generation

- Four kinds of program points result in constraints:
  - Declarations
  - Assignments
  - Function Calls
  - Function Return

Constraint Generation

- Four variables for each string buffer
  - `buf_len_max, buf_len_min`
  - `buf_alloc_max, buf_alloc_min`
- Operations on a buffer
  - strcpy (tgt, src)
    - $tgt\_len\_max \geq src\_len\_max$
    - $tgt\_len\_min \leq src\_len\_min$

Constraint Generation



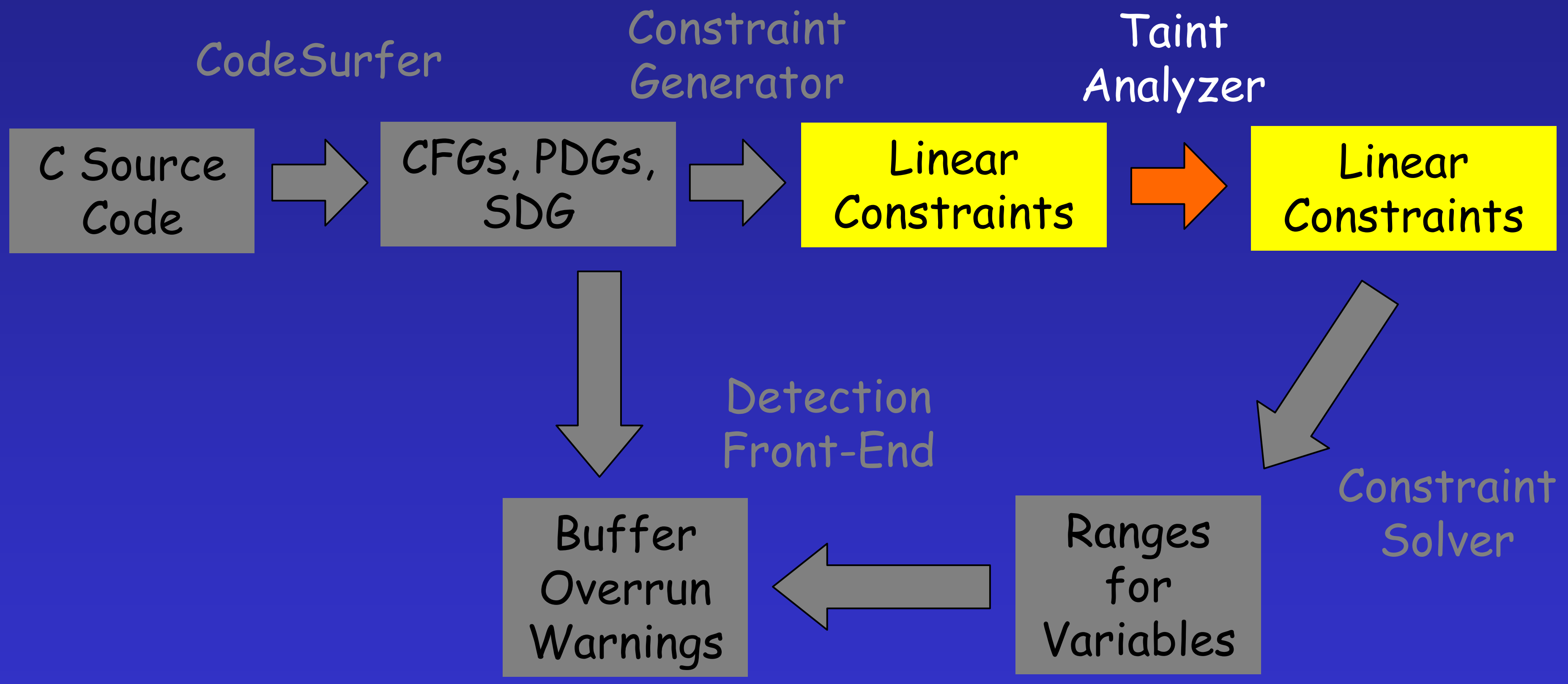
Constraint Generation Methods

- Order of statements:
  - *Flow-Sensitive* Analysis:
    - Respects program order
  - *Flow-Insensitive* Analysis:
    - Does not respect program order
- Function Calls:
  - *Context-Sensitive* modeling of functions:
    - Respects the call-return semantics
  - *Context-Insensitive* modeling of functions:
    - Ignores call-return semantics => imprecise

Constraint Generation

- Constraints generated by our tool:
  - Flow-insensitive
  - Context-sensitive for some library functions
  - Partly Context-sensitive for user defined function
    - Procedure summaries

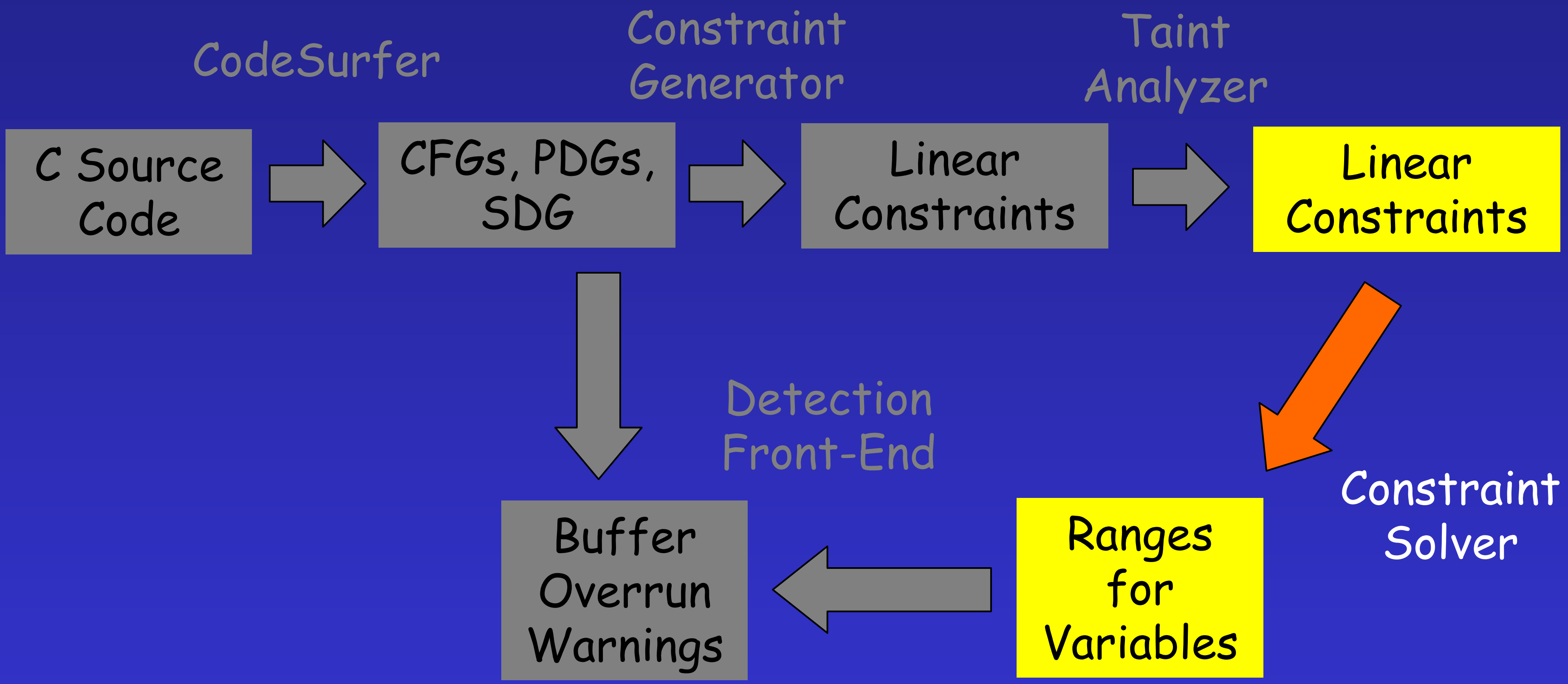
Taint Analysis



Taint Analysis

- Removes un-initialized constraint variables
  - Un-modeled library calls
  - Un-initialized program variables
- Required for solvers to function correctly

Constraint Solvers

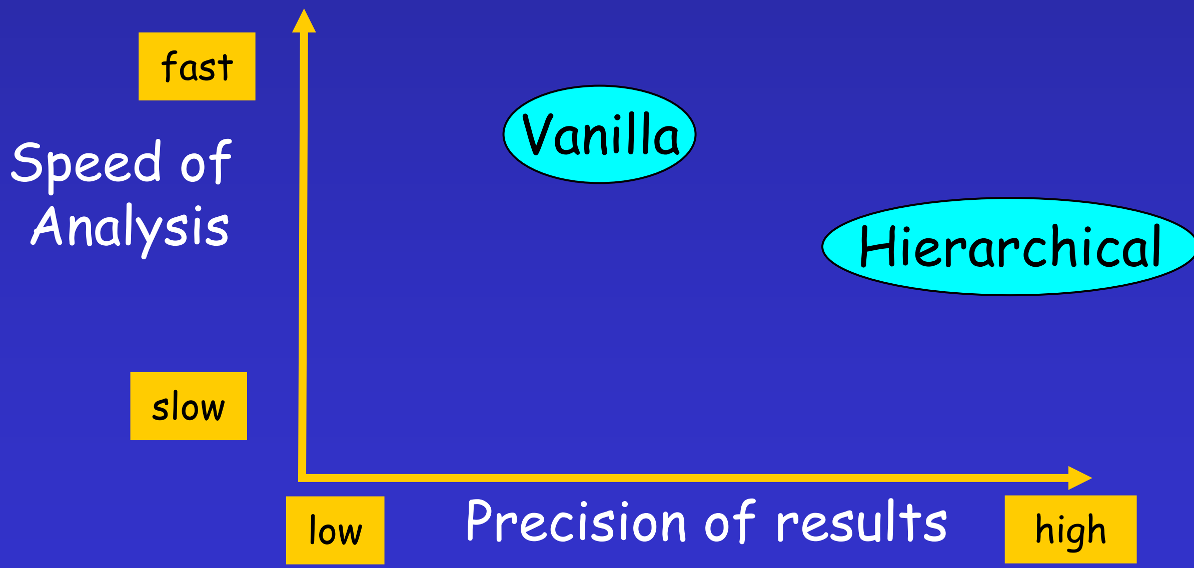


Constraint Solvers

- Abstract problem:
  - Given a set of constraints on `max` and `min` variables
  - Get tightest possible fit satisfying all the constraints
- Our approach:
  - Model and solve as a linear program

Constraint Solvers

- We have developed two solvers:
  - Vanilla solver
  - Hierarchical solver



Linear Programming

- An objective function F
- Subject to: A set of constraints C
- Example:

```
Maximize: x
Subject to:
    x <= 3
```

Why Linear Programming?

- Can support arbitrary linear constraints
- Commercial linear program solvers are highly optimized and fast
- Use of *linear programming duality* for diagnostics
  - Can be used to produce a "witness" trace leading to the statement causing the buffer overrun

Vanilla Constraint Solver

- Goal: Obtain values for buffer bounds
- Modeling as a Linear Program

Minimize: max variable
Subject to:
    Set of Constraints

And

Maximize: min variable
Subject to:
    Set of Constraints

Least Upper Bound

Greatest Lower Bound

Tightest possible fit

Vanilla Constraint Solver

- *However,* it can be shown that:

  Min: Σ (max vars) - Σ(min vars)

  Subject to: Set of Constraints

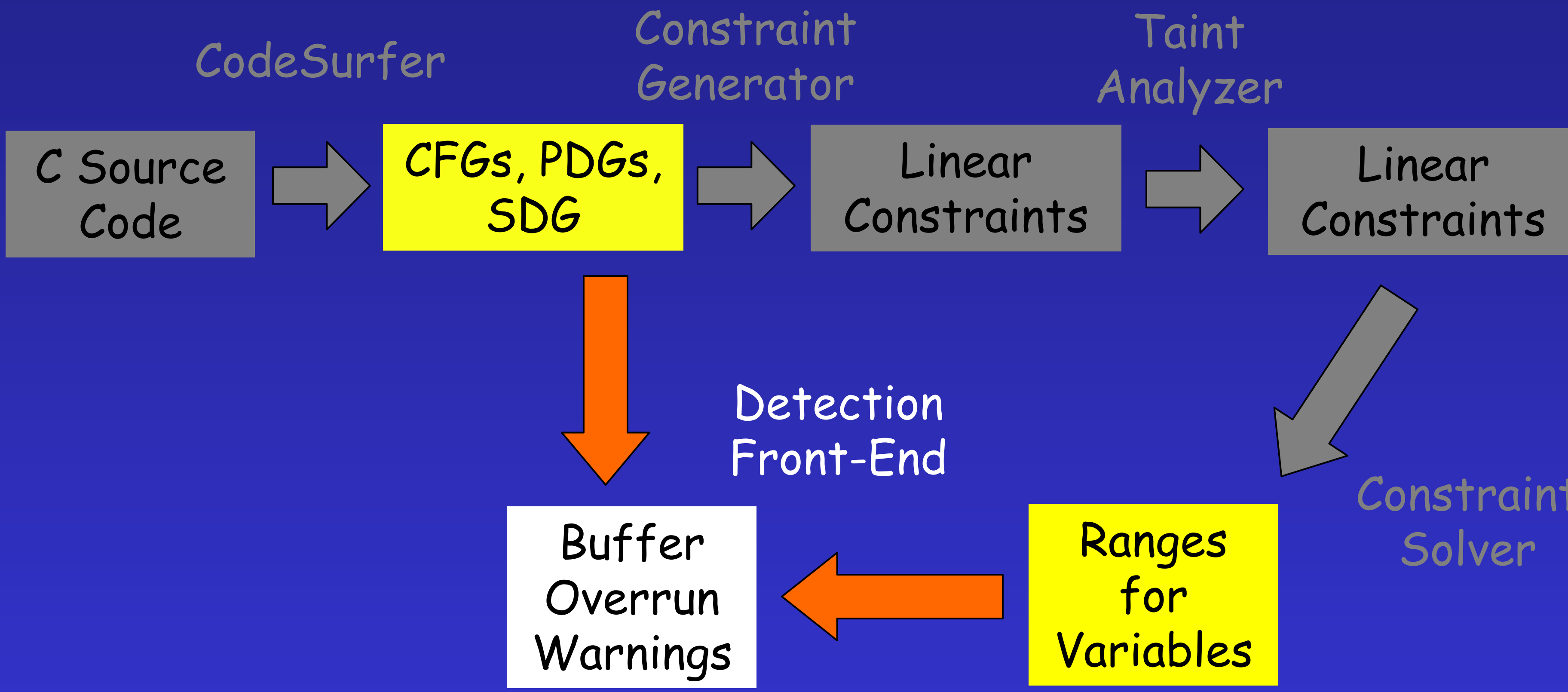
  yields the same solution for each variable

- Solve just *one Linear Program* and get values for all variables!

Vanilla Constraint Solver

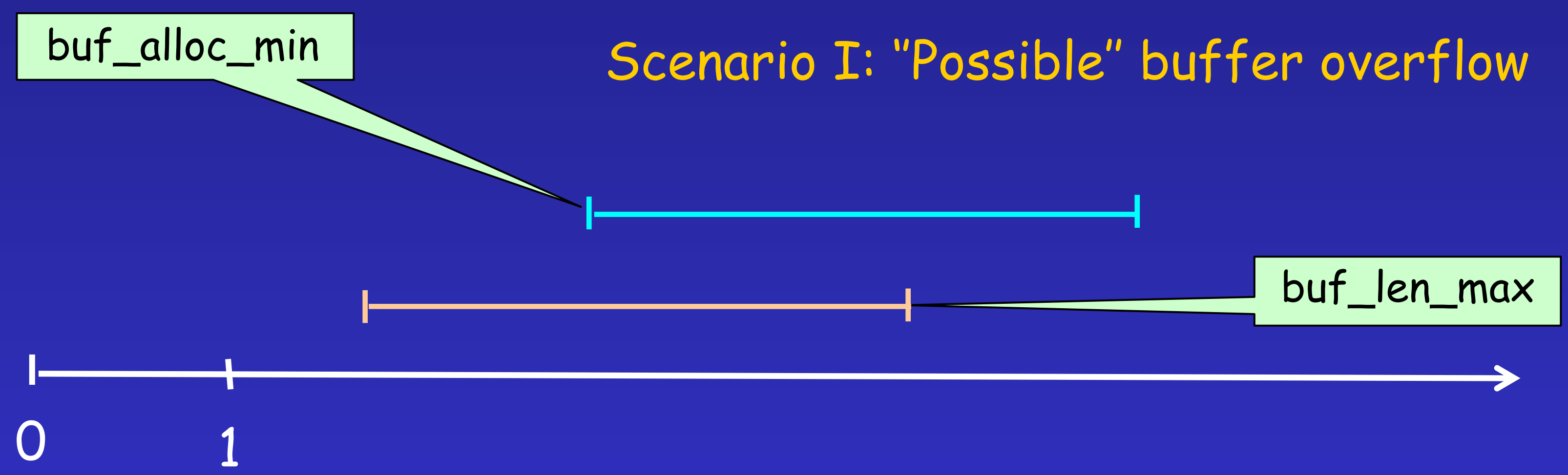
- Why is this method imprecise?
  - *Infeasible* linear programs
  - Why do such linear programs arise?
- Deals with infeasibility using an approximation algorithm
- See paper for details

Detection Front-End



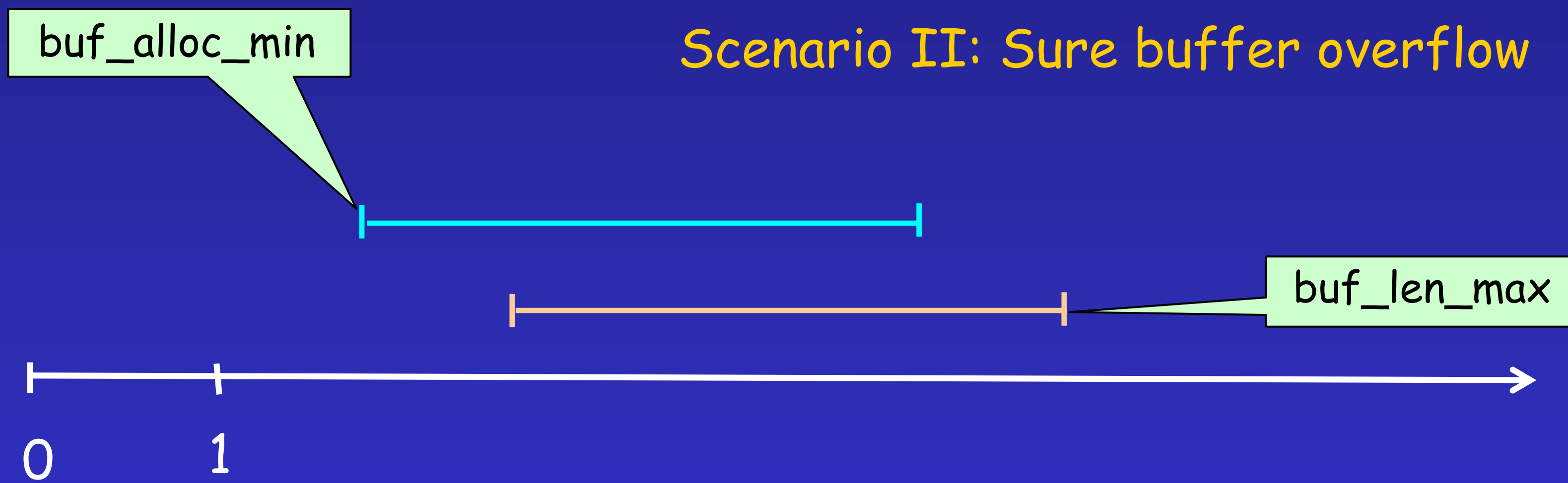
Detection Front-End

Scenario I: "Possible" buffer overflow



Detection Front-End

Scenario II: Sure buffer overflow



Roadmap of Talk

- Tool Architecture
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  - Constraint Resolution
  - Producing Warnings
- Adding Context Sensitivity
- Results
- Future work and Conclusions

Context-Insensitive Analysis

```
foo () {
    int x;
    x = foobar(5);
}
```

```
bar () {
  int y;
  y = foobar(30);
}
```

```
int foobar (int z) {
    int i;
    i = z + 1;
    return i;
}
```

Context-Insensitive Analysis

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foo () {
    int x;
    x = foobar(5);
}
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bar () {
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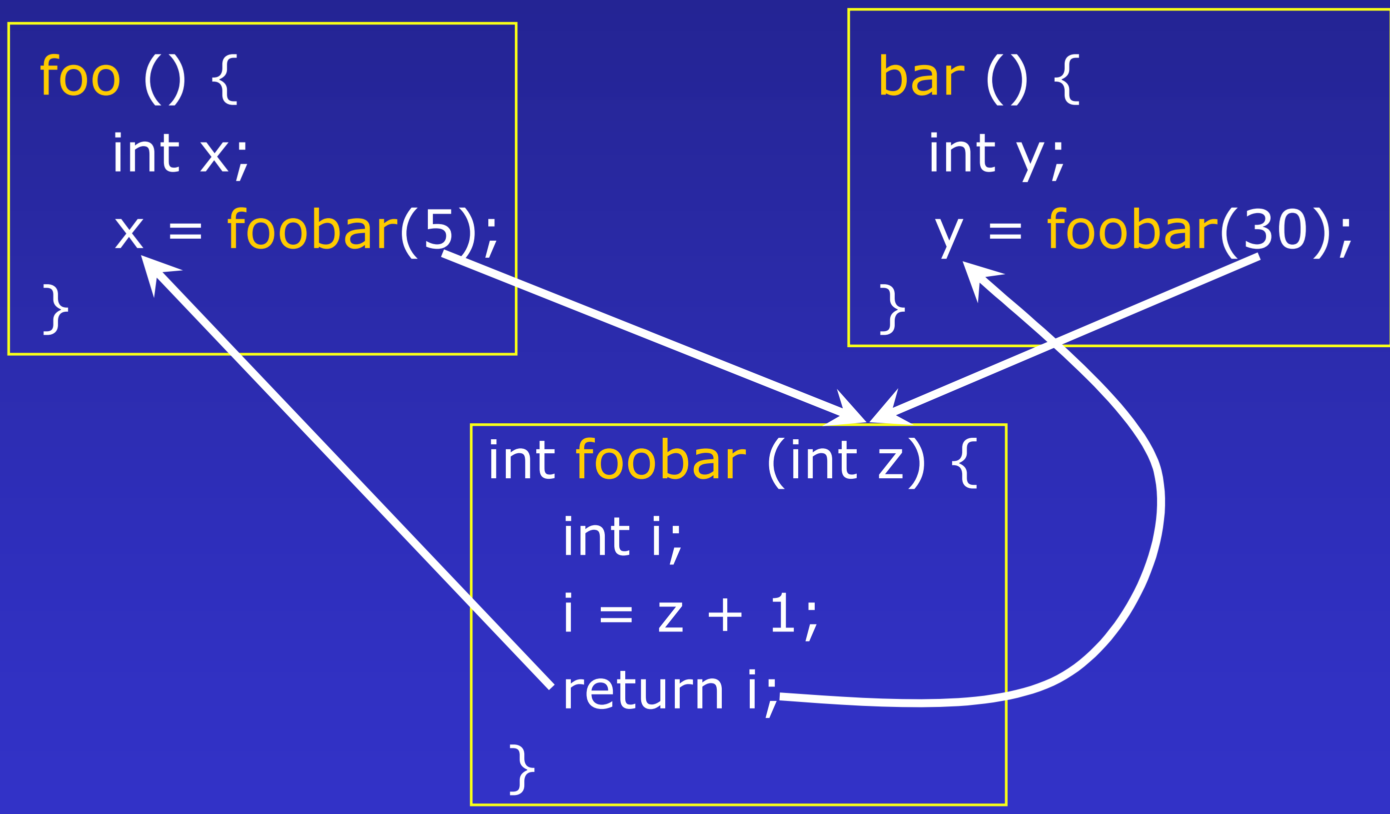
Context-Insensitive Analysis



Context-Insensitive Analysis

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foo () {
    int x;
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bar () {
   int y;
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```
int foobar (int z) {
    int i;
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    return i;
}
```

False Path

Result: x = y = [6..31]

Adding Context Sensitivity

- Make user functions context-sensitive
  - e.g. wrappers around library calls
- Inefficient method: Constraint inlining
  - ☺ Can separate calling contexts
  - ☹ Large number of constraint variables
  - ☹ Cannot support recursion

Adding Context Sensitivity

- Efficient method: Procedure summaries
- Basic Idea:
  - Summarize the called procedure
  - Insert the summary at the call-site in the caller
  - Remove false paths

Adding Context Sensitivity

```
foo () {
    int x;
    x = foobar(5);
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bar () {
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```

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int foobar (int z) {
    int i;
    i = z + 1;
    return i;
}
```

Adding Context Sensitivity

```
foo () {
    int x;
    x = foobar(5);
}
```

x = 5 + 1

```
bar () {
    int y;
    y = foobar(30);
}
```

y = 30 + 1

```
int foobar (int z) {
    int i;
    i = z + 1;
    return i;
}
```

Summary: i = z + 1

Adding Context Sensitivity

```
foo () {
    int x;
    x = foobar(5);
}
```

```
bar () {
  int y;
  y = foobar(30);
}
```

```
int foobar (int z) {
    int i;
    i = z + 1;
    return i;
}
```

Jump Functions

Adding Context Sensitivity

```
foo () {
    int x;
    x = foobar(5);
}
```

```
bar () {
    int y;
    y = foobar(30);
}
```

```
int foobar (int z) {
    int i;
    i = z + 1;
    return i;
}
```

No false paths ☺

x = [6..6]

y = [31..31]

i = [6..31]

Adding Context Sensitivity

- Computing procedure summaries:
  - In most cases, reduces to a shortest path problem
  - Other cases, Fourier-Motzkin variable elimination

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- **Results**
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Results: Overruns Identified

Application	LOC	Warnings	Vulnerability	Detected?
WU-FTPD-2.5.0	16000	139	CA-1999-13	Yes
WU-FTPD-2.6.2	18000	178	None	14 New
Sendmail-8.7.6	38000	295	Identified by Wagner et al.	Yes
Sendmail-8.11.6	68000	453	CA-2003-07	Yes, but…

Results: Context Sensitivity

- WU-FTPD-2.6.2: 7310 ranges identified
- Constraint Inlining:
  - 5.8x number of constraints
  - 8.7x number of constraint variables
  - 406 ranges refined in at least one calling context
- Function Summaries:
  - 72 ranges refined

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Conclusions

- Built a tool to detect buffer overruns
- Incorporated in a program understanding framework
- Current work:
  - Adding Flow Sensitivity
  - Reducing the number of false warnings while still maintaining scalability

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