Systems and Internet Infrastructure Security

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Static Analysis Basics II

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Outline

- More background
  - Pushdown Systems
  - Boolean Programs
  - Enable more refined dataflow analysis
- Metacompilation
- Control Flow and Data Flow Integrity

Pushdown Systems

- To encode ICFGs
  - What are ICFGs?
  - Why are they necessary for dataflow analysis?
  - What is the major challenge in using ICFGs in dataflow?
  - Other challenges?

Pushdown Systems

- Consists of
  - A finite set of states
  - A finite set of stack symbols
  - A finite set of rules
    - Which define a transition relation

Modeling Control Flow

- One state
- Each ICFG node is a stack symbol
- Each ICFG edge is represented by a rule
  - $(p, e_{main}) \rightarrow (p, n_1)$
  - $(p, n_3) \rightarrow (p, e_f n_4)$
  - $(p, n_{12}) \rightarrow (p, x_f)$
  - $(p, x_f) \rightarrow (p, epsilon)$
- PDSs with a single control location are called context-free processes

Pushdown Systems

- A configuration is a pair (node, stack)
  - Where we are currently and why
  - Pre and post-configurations are important
    - Backward and forward reachability over the transition relation

Find All Reachable Configurations

- Start with a set of configurations
  - Can be used for assertion checking statically (Phil)
- Number of configurations in a pushdown system is unbounded – use finite automata to describe regular sets of configurations
- Why?
  - Symbolic Reachability Analysis of Higher-Order Context-Free Processes – Bouajjani and Meyer
  - http://igm.univ-mlv.fr/~ameyer/binaires/fsttcs04.pdf

Find All Reachable Configurations

- Represent sets of configurations as
- P-automaton (FSA)
  - States (superset of PDS states)
  - Stack symbols
  - Transition relation
  - Start and final states
- What is it missing from the PDS representation?

Find All Reachable Configurations

- Compute post*(C) and pre*(C)
- Take a P-automaton that accepts a set of configurations C
  - Produces an automaton that accepts the pre and post configurations
- Saturation procedures
  - Add transitions to A until no more can be satisfied

Find All Reachable Configurations

- Prestar
  - If *(p, v)* → *(p', w)* and *p'* $\rightarrow_w$ *q* in *A*
    - *v in Stack, w in Stack**
  - Then add transition *(p, v, q)*
- Why does this enable finding the backward reachable state for a configuration?
  - Efficient algorithms for modeling pushdown systems, Esparza et al (ref 107)

Find All Reachable Configurations

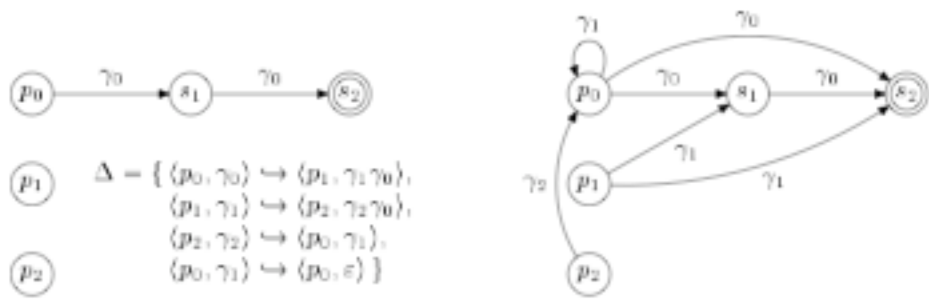


Fig. 1. The automata $\mathcal{A}$ (left) and $\mathcal{A}_{pre^*}$ (right)

Find All Reachable Configurations

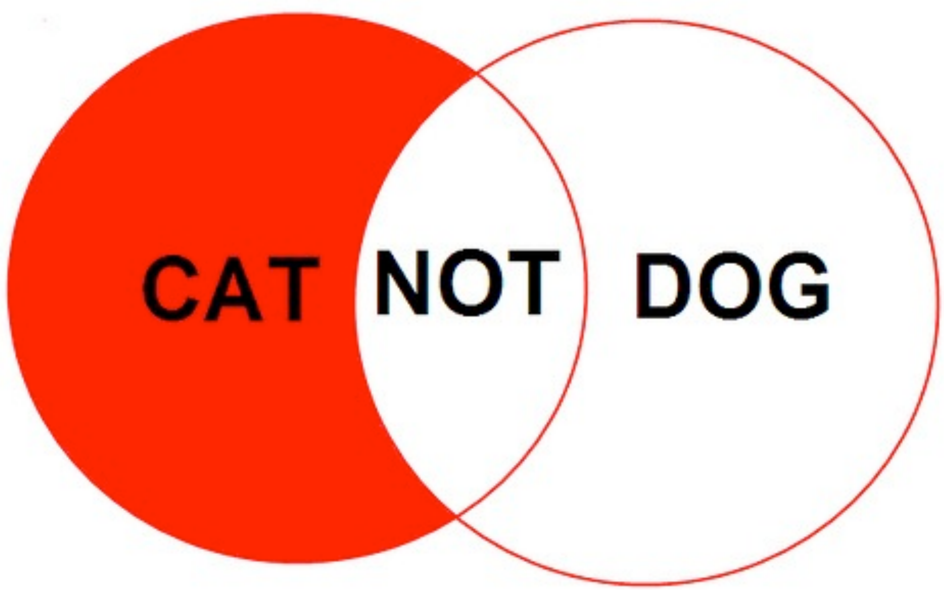
- Poststar
  - Phase I: For each (p', v') s.t. P contains at least one rule $(p, v) \rightarrow (p', v', v'')$, add new state $p'_{v'}$
  - Phase II:
    - If $(p, v) \rightarrow (p', epsilon)$ in rules $p \rightarrow_v q$, then $(p', epsilon, q)$
    - If $(p, v) \rightarrow (p', v')$ in rules $p \rightarrow_v q$, then (p', v', q)
    - If $(p, v) \rightarrow (p', v'v'')$ in rules $p \rightarrow_v q$, then (p', v', pv') and $(p'_{v'}, v'', q)$
- Figure 2.7

Find All Reachable Configurations

- Fig 2.7
- Phase 1: Add states
  - $(p, n_3) \rightarrow (p, e_f n_4)$ results in P_{ef}
  - (p, n_7) also – but same state
- Phase 2: Add transitions
  - $(p, x_f) \rightarrow (p, epsilon) \rightarrow (p, epsilon, p_{ef})$ and $(p, epsilon, q)$
  - $(p, n_8) \rightarrow (p, n_9) \rightarrow (p, n_9, q)$
  - $(p, n_3) \rightarrow (p, e_f n_4)$ and $p \rightarrow q$, $\rightarrow (p, e_f, p_{ef})$ and (p, n_4, q)

Boolean Programs

- Program that only uses boolean data types and fixed-length vectors of booleans
  - Finite set of globals and local variables



Boolean Programs

- Let *G* be the valuations of globals
- Val_i be the valuations of the locals in procedure *i*
- L is local states
  - Program counter
  - Val_i
  - Stack
- Assignment statement is binary relation that states how the values *G* and Val_i (variables in scope) may change

Encode Boolean Program in PDS

- Why?
- Changes
  - Use P to encode globals
  - Use stack alphabet to encode local vars
- Model
  - (N_i is control nodes in i^{th} procedure)
  - P is set to G
  - Stack symbols are union of N_i X Val_i
  - Rules for assignments, calls, returns

Vulnerability

- How do you define computer ‘vulnerability’?
  - *Flaw*
  - *Accessible to adversary*
  - *Adversary has ability to exploit*

Vulnerability

- How do you define computer 'vulnerability'?
  - *Flaw – Can we find flaws in source code?*
  - *Accessible to adversary – Can we find what is accessible?*
  - *Adversary has ability to exploit – Can we find how to exploit?*

Bugs

- Known incorrect functions
  - Dereference after free
  - Double free
- Often have known patterns
  - Can we express and check

Metacompilation

A System and Language for Building System-Specific, Static Analyses

Seth Hallem, Benjamin Chelf, Yichen Xie, and Dawson Engler

Stanford University

Metacompilation

Overview

- Goal: find as many bugs as possible
  - Allow users of our system to write the analyses
- Implementation: tool with two parts
  - Metal - the language for writing analyses
  - xgcc - the engine for executing analyses
- System design goals
  - Metal must be easy to use and flexible
    - we have written over 50 checkers, found 1000+ bugs in Linux, OpenBSD and still counting
  - xgcc must execute Metal extensions efficiently
  - xgcc must not restrict Metal extensions *too* much

Metacompilation

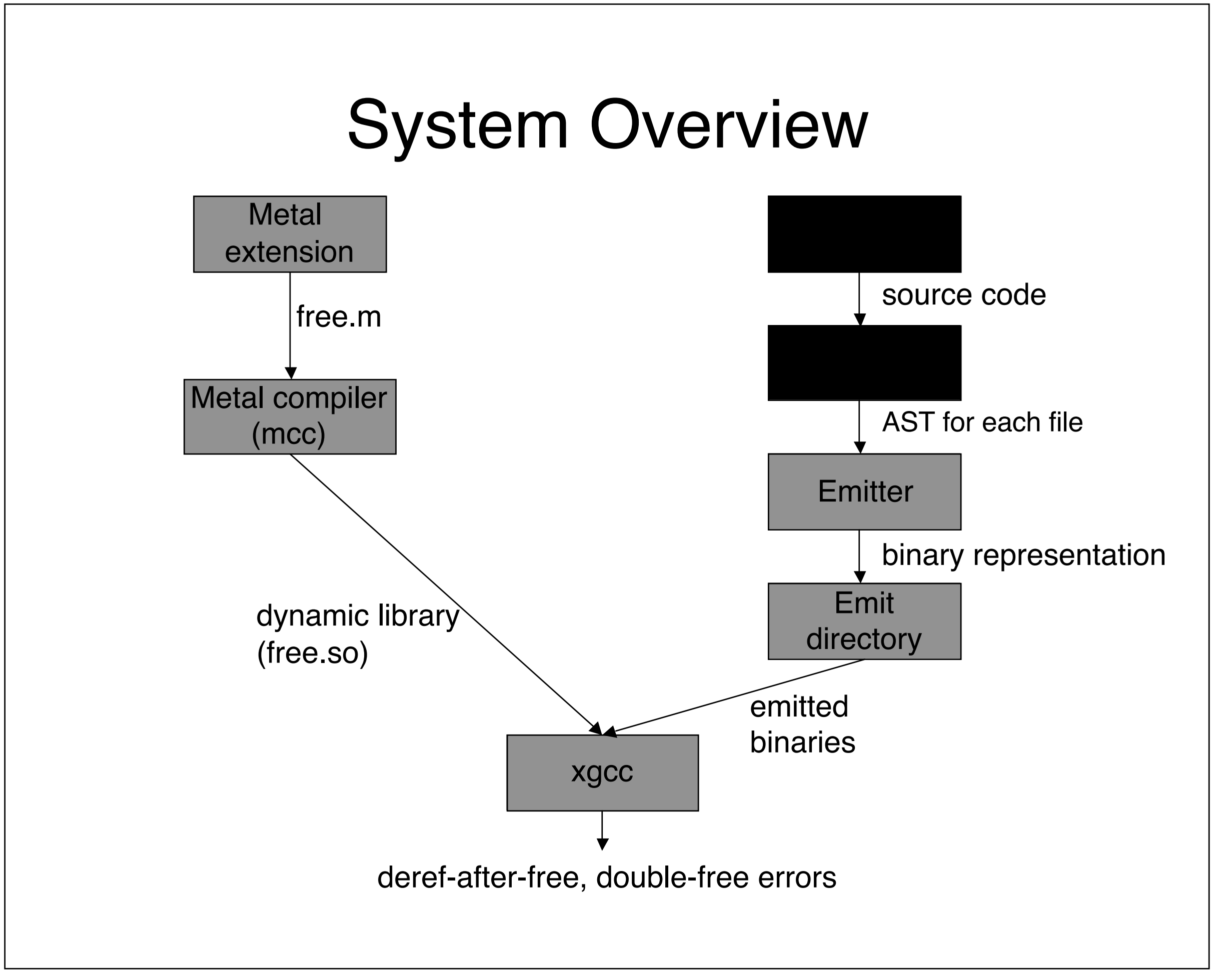
Overview

- The goal of our research is to find as many bugs in real systems as possible
- Insight: many rules are system-specific.
  - The number of rules that apply to all programs is very small; violations of these generic rules are hard to find.
    - E.g. memory errors, race conditions, etc.
- Programmers know the rules their code obeys
- A system that allows programmers to specify these rules will find lots of bugs

Metacompilation

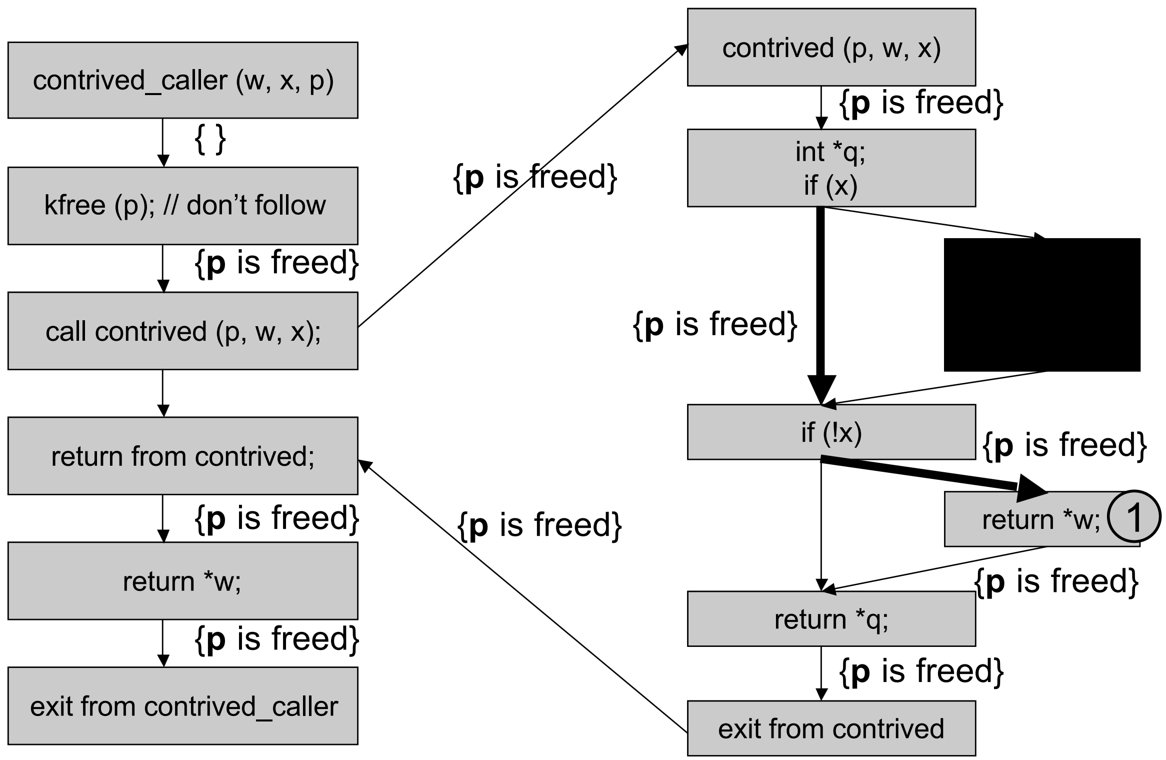
```
int contrived_caller (int *w, int x, int *p) {
    kfree (p);
    contrived (p, w, x);
    return *w;              // deref after free (3)
}

int contrived (int *p, int *w, int x) {
    int *q;
    if (x) {
        kfree (w);
        q = p;
        p = 0;
    }
    if (!x)
        return *w;  // safe (1)
    return *q;       // deref after free (2)
}
```

Metacompilation

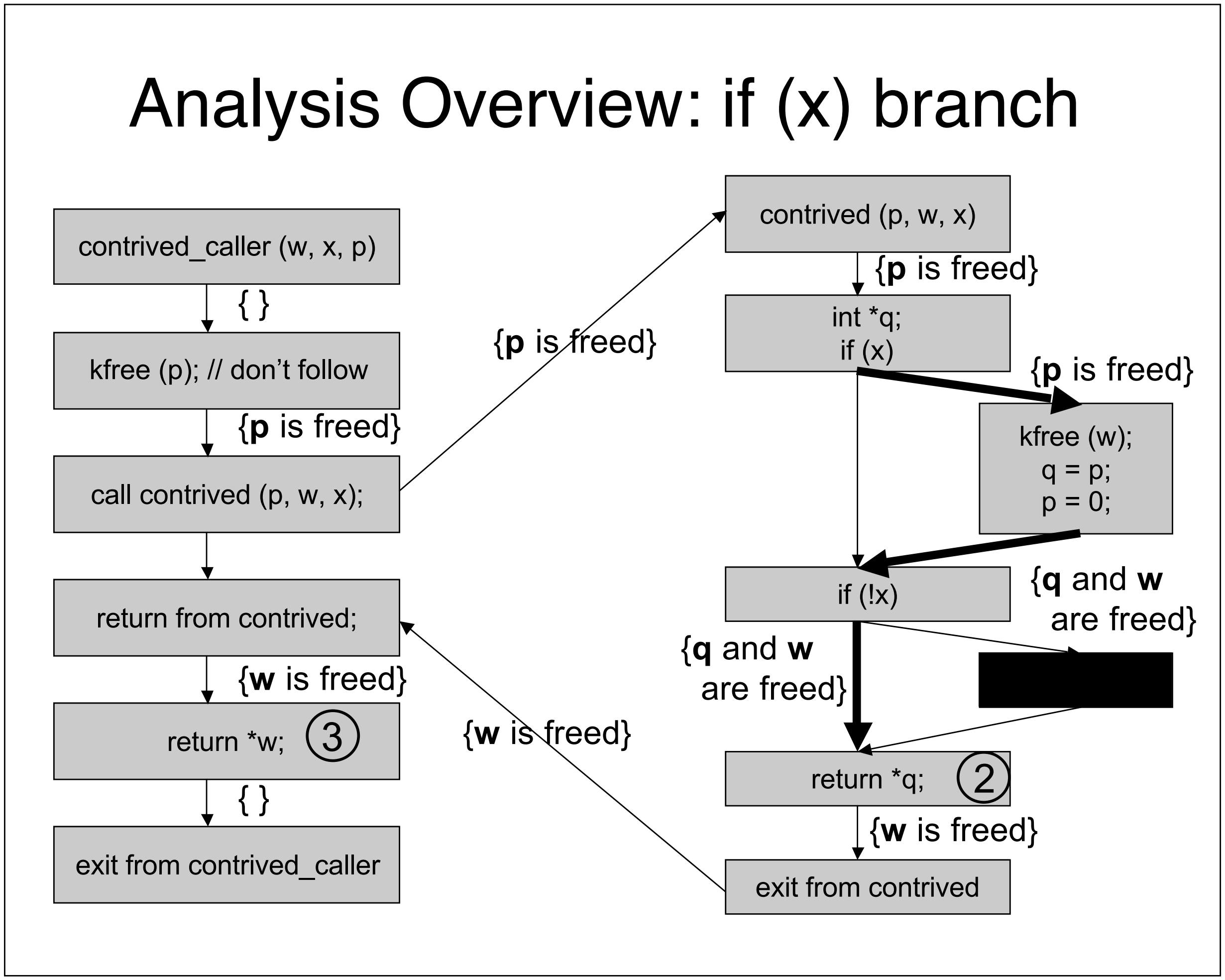


Metacompilation

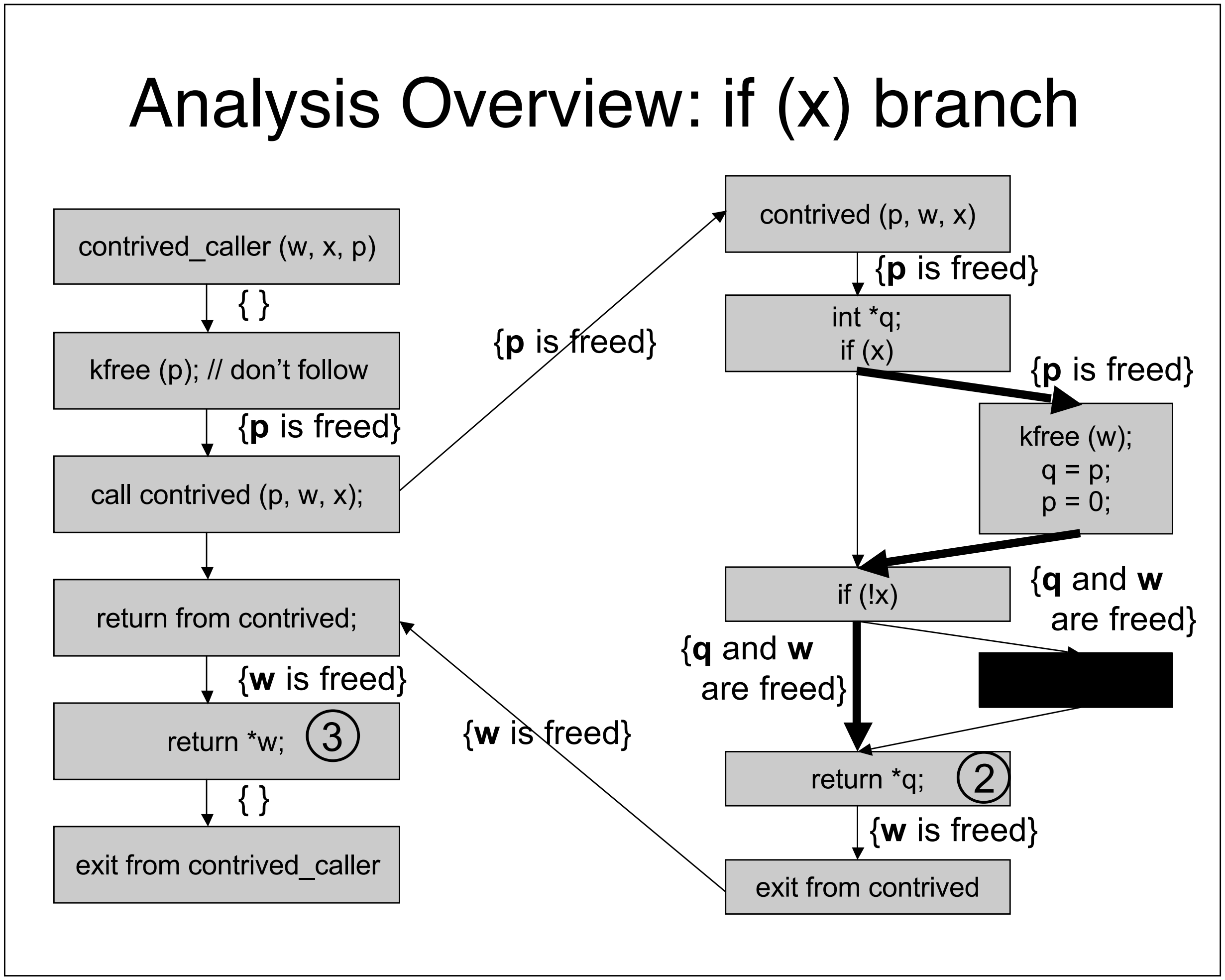
Analysis Overview: if (!x) branch



Metacompilation



Metacompilation



Metacompilation

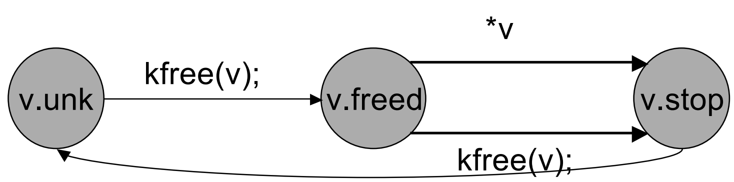
Metal extensions

- State machine abstraction
  - SMs have patterns, states, transitions, and actions
- Why is Metal easy to use?
  - SMs are a familiar concept to programmers
  - Patterns specify interesting source constructs in the source language
- Why is Metal flexible?
  - Actions are escapes to arbitrary C code that execute whenever a transition executes
  - Main restriction is determinism

Metacompilation

Example: the free checker

- Looks for deref-after-free, double free
- Free checker is a collection of SMs
- Each SM tracks a single program object



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Metacompilation

Metal states

- Two types of states
  - Global: “interrupts are disabled”
  - Variable-specific: “pointer p is freed”
- States are bound to state variables

```
sm free-check {
        state decl any_pointer v;
        start: { kfree (v) } ==> v.freed;
        v.freed: { *v } ==> v.stop,
                { err (“dereferenced %s after free!”, mc_identifier (v)); }
        | { kfree (v) } ==> v.stop,
                { err (“double free of %s!”, mc_identifier (v)); }
        ;
}
```

Metacompilation

Metal patterns

- Syntactic matching: literal AST match
- Semantic matching: wildcard types

```
sm free-check {
  state decl any_pointer v;
  start:    { kfree (v) } ==> v.freed;
  v.freed:{ *v } ==> v.stop,
             { err ("dereferenced %s after free!", mc_identifier (v)); }
           | { kfree (v) } ==> v.stop,
             { err ("double free of %s!", mc_identifier (v)); }
           ;
}
```

Metacompilation

Metal transitions and actions

- Specify with source state, pattern, destination state
- Actions execute when transition occurs
  - Report errors, extend analysis (e.g., statistical)

```
sm free-check {
  state decl any_pointer v;
  start: { kfree (v) } ==> v.freed;
  v.freed: { *v } ==> v.stop,
              { err (“dereferenced %s after free!”, mc_identifier (v)); }
           | { kfree (v) } ==> v.stop,
              { err (“double free of %s!”, mc_identifier (v)); }
           ;
}
```

Metacompilation

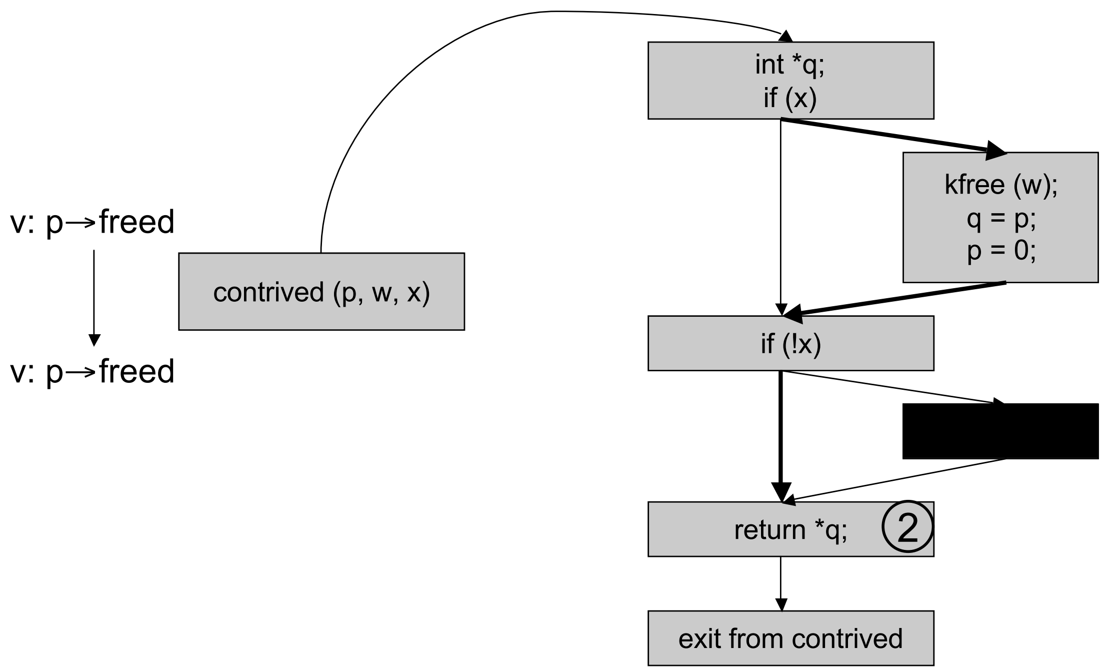
Executing Metal SMs

- Intraprocedural analysis:
  - Depth-first-search + caching
  - Cache at the block level
    - contains union of all “facts” seen at that block
  - On cache hit, abort the current path, backtrack
- Interprocedural analysis
  - Summarize the effects of analyzing large portions of the code
  - Use summaries whenever possible

Metacompilation

Executing Metal SMs: DP Edges

- Derived from “Precise Interprocedural Dataflow Analysis via Graph Reachability”; Reps, Horowitz, Sagiv 1995



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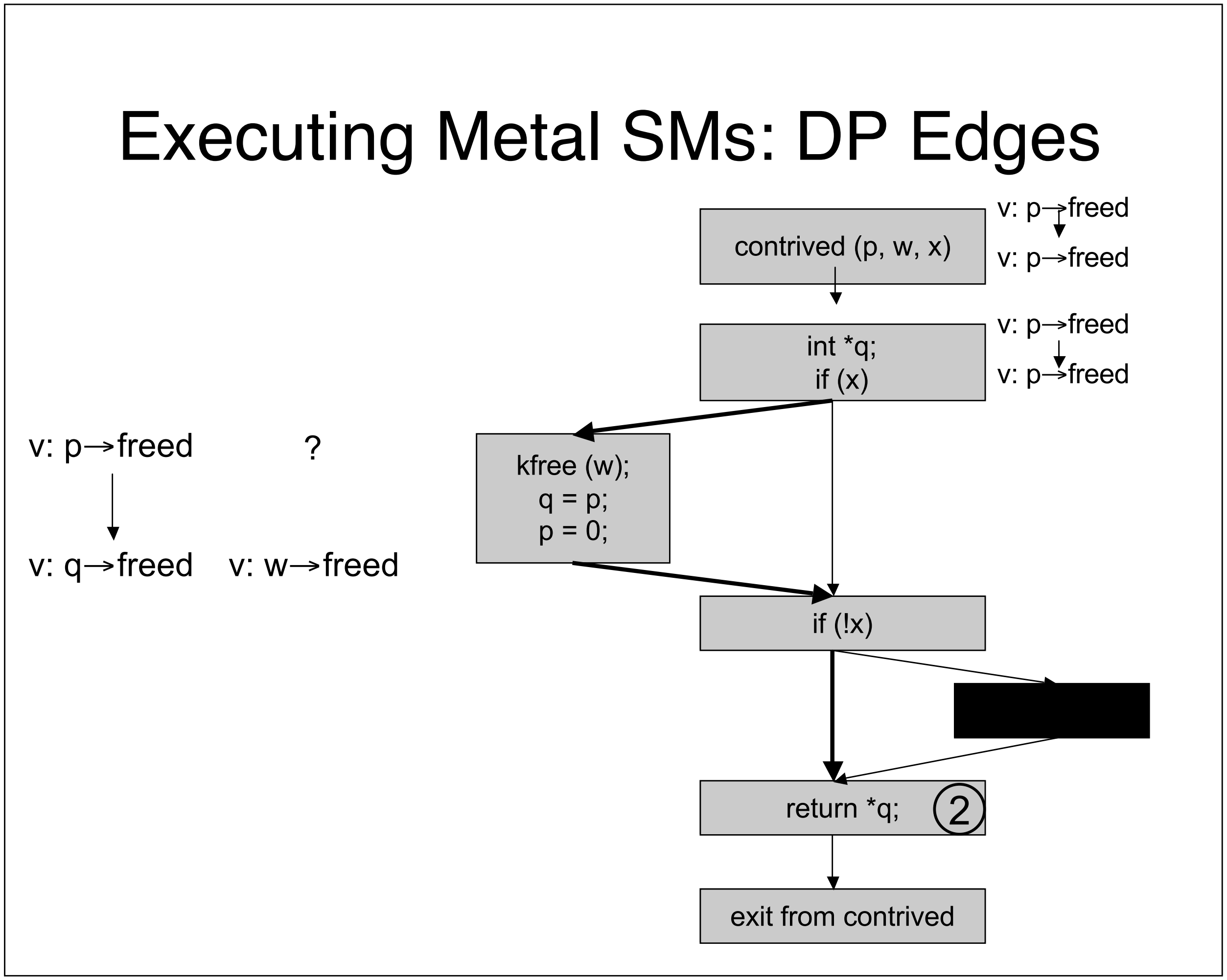

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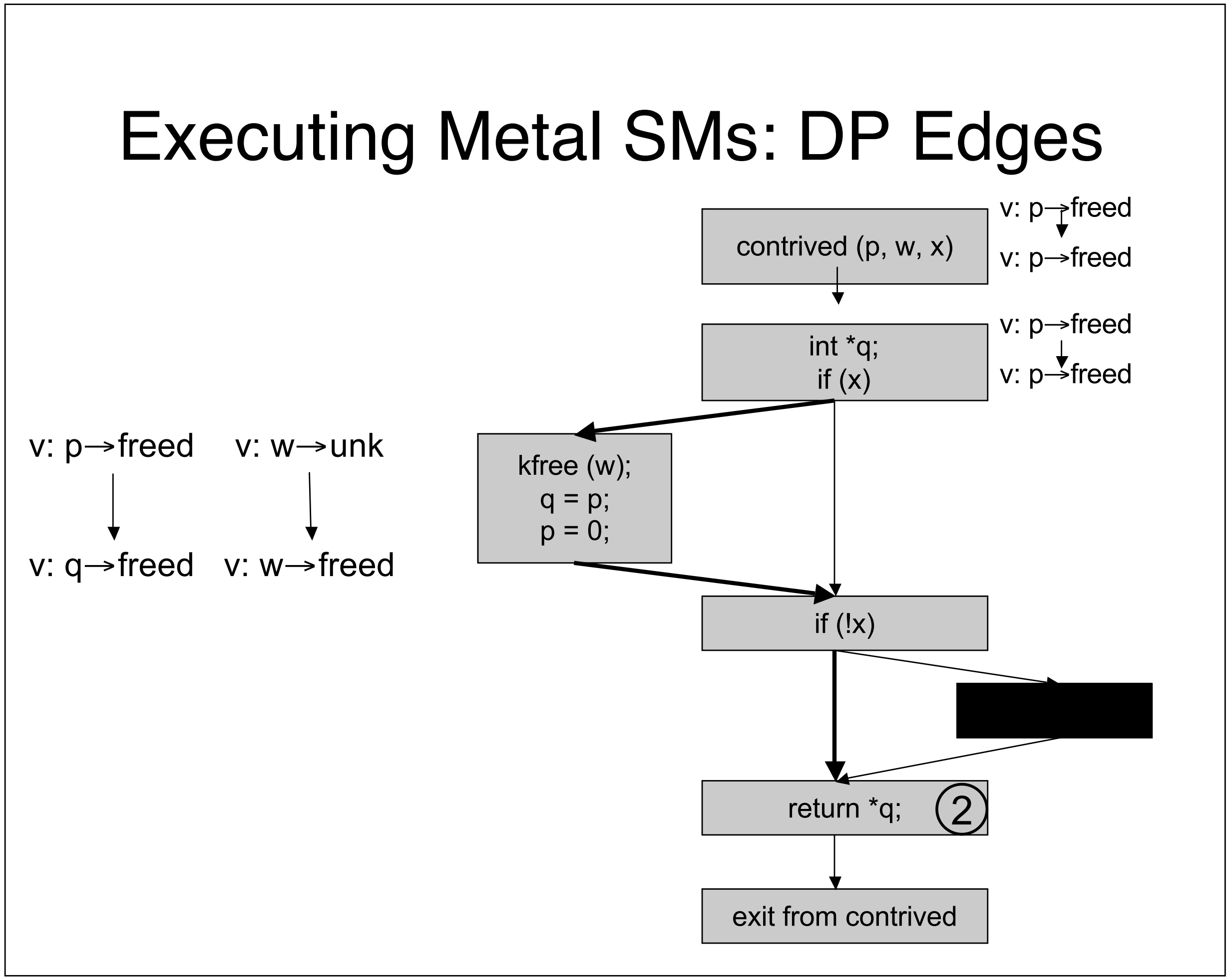
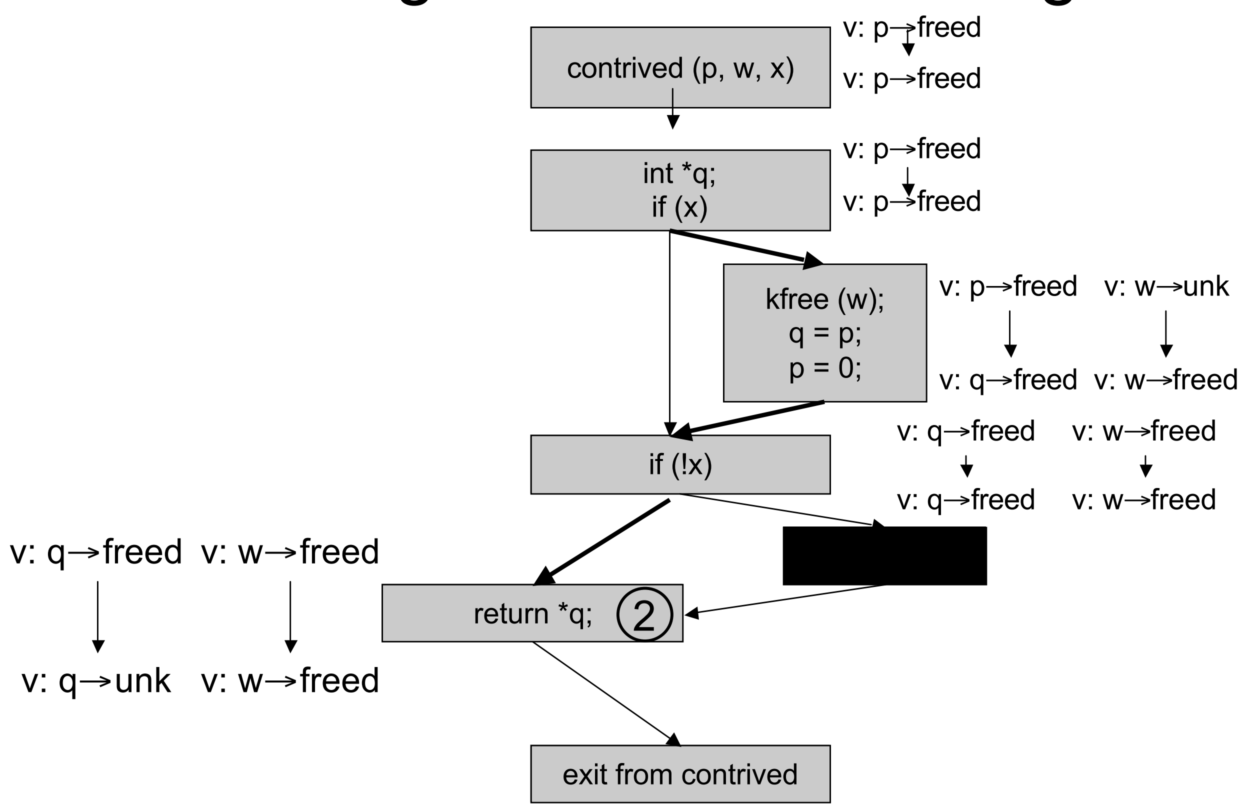


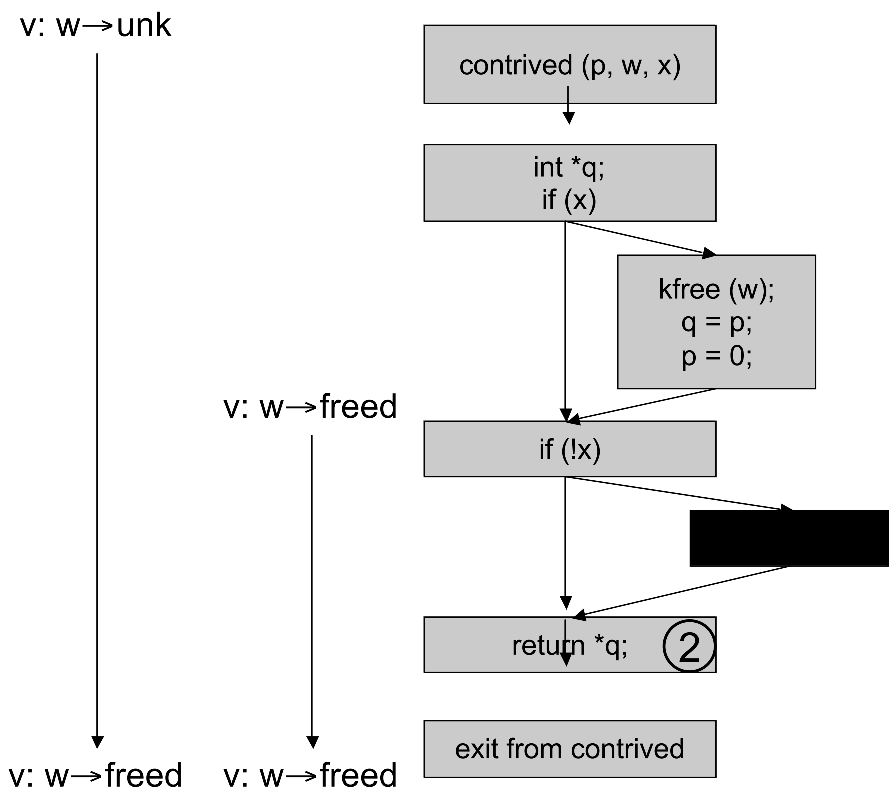
Metacompilation

Executing Metal SMs: DP Edges



Metacompilation

Example: Memoizing Edges



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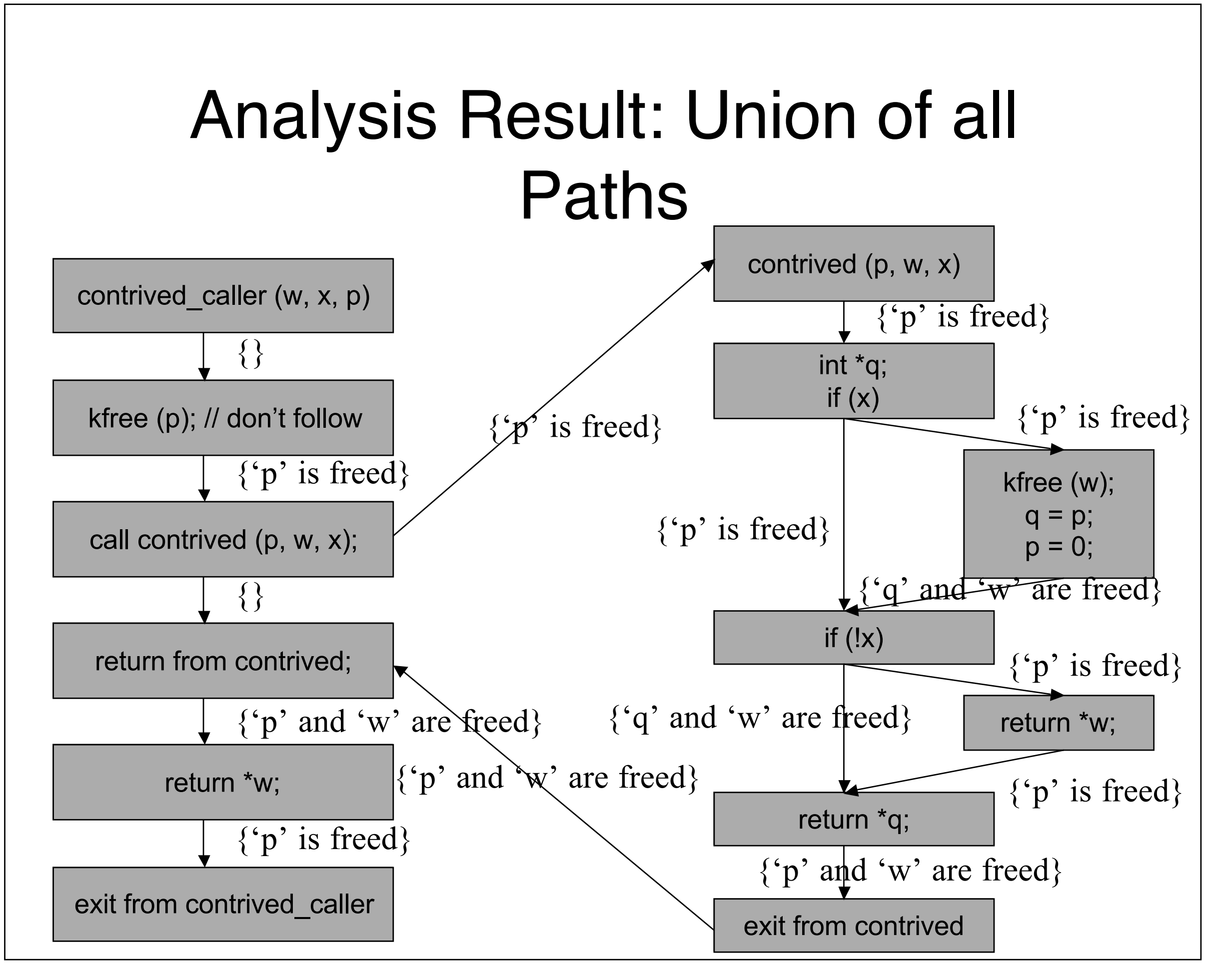

Metacompilation

Interprocedural Analysis

- Start at each entry point to the callgraph
  - initially we do not know any facts
- Traverse CFG for each function depth-first
- At the end of an intraprocedural path, relax edges
- At a function call, analyze call with new facts
- At return, apply edges to extension state

Metacompilation

False-Path Pruning

```
int f (int x, int z) {
        int a, b, p, q, y;
        p = x;
        q = 5;
        a = x;
        b = 5;
        if (z  == (p + q)) {
                y = a + b;
                if (z != y) {
                        . . .
                }
        . . .
        }
}
```

- Know nothing.
- Track p = x.
- Track q = 5.
- Track a = x.
- Track b = 5.
- Track z = p + q.
- Track y = a + b.
- ??

Metacompilation

False-Path Pruning

```
int f (int x, int z) {
        int a, b, p, q, y;
        p = x;           <----------  {p, x}
        q = 5;           <----------  {q, 5}
        a = x;           <----------  {a, x}
        b = 5;           <----------  {b, 5}
        if (z  == (p + q)) {
                y = a + b;     <----------  {z, p + q}
                if (z != y) {  <----------  {y, a + b}
                        . . .  <----------  ??
                }
        . . .
        }
}
```

More False Positives

- Simple value flow
  - Tracks all value flow through direct assignment flow sensitively
  - Ignores indirect value flow
    - p = q implies p, q are aliases but not *p, *q
  - Tracks structure fields, pointer arithmetic

Metacompilation

Unsoundness

- Unsound because:
  - No conservative alias analysis
  - Do not handle recursion soundly
- Benefits of unsoundness
  - Goal is to find as many bugs as possible
  - For many properties conservative assumptions cause an explosion of false positives
- Future goal: precise unsoundness

Metacompilation

Ranking

- Ranking: we find too many errors to inspect
  - Rank most likely, easiest-to-diagnose errors first
  - Statistical ranking: use statistical test of significance to rank rules we check
    - reliable rules are usually followed

Metacompilation

Conclusion

- Evaluating our approach
  - Flexible: over 50 checkers
  - Easy-to-use: Metal provides abstraction, sugar
    - unsound analysis is easy
  - Effective: 1000+ real bugs, still finding more
  - What makes our tool effective?
    - does just enough analysis to find bugs
    - often trade precision for speed/flexibility
    - aliasing: conservative is too imprecise; more aggressive analysis is helpful

Control and Data Flow Integrity

- How do they work?
- Are they Sound?

Summary

- Introduction to Pushdown Systems and Boolean Programs
  - Application to Dataflow Analysis
  - Prove to yourself
- Application of Static Analysis to Bug Finding
  - Metacompilation
- And Enforcement of Program Execution Integrity
  - Control Flow Integrity
  - Data Flow Integrity