Improving Software Quality with Type Qualifiers

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Introduction

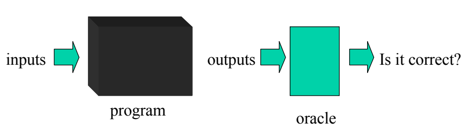
- Ensuring that software is reliable is hard
  - And doing so is important

[T]he national annual costs of an inadequate infrastructure for software testing is estimated to range from $22.2 to $59.5 billion.

-- NIST Planning Report 02-3, May 2002

Current Practice

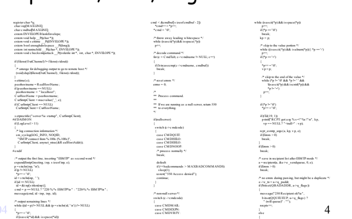
- Testing
  - Make sure program runs correctly on set of inputs



  - Drawbacks: Expensive, difficult, hard to cover all code paths, no guarantees

Current Practice (cont'd)

- Code Auditing
  - Convince someone else your source code is correct
  - Drawbacks: Expensive, hard, no guarantees



And If You're Worried about Security…

A malicious adversary is trying to exploit anything you miss!

What more can we do?

Tools for Software Quality

- What more can we do?
  - Build tools that analyze source code (static analysis)
    - Reason about all possible runs of the program
  - Check limited but very useful properties
    - Eliminate categories of errors
    - Let people concentrate on the deep reasoning
  - Develop programming models
    - Avoid mistakes in the first place
    - Encourage programmers to think about and make manifest their assumptions

Oops — We Can't Do This!

- Rice's Theorem: No computer program can precisely determine anything interesting about arbitrary source code
  - Does this program terminate?
  - Does this program produce value 42?
  - Does this program raise an exception?
  - Is this program correct?

The Art of Static Analysis

- Programmers don't write arbitrarily complicated programs
- Programmers have ways to control complexity
  - Otherwise they couldn't make sense of them
- Target: Be precise for the programs that programmers want to write
  - It's OK to forbid yucky code in the name of safety

Tools Need Specifications

```
spin_lock_irqsave(&tty->read_lock, flags);
put_tty_queue_nolock(c, tty);
spin_unlock_irqrestore(&tty->read_lock, flags);
```

- Goal: Add specifications to programs

  In a way that...
  - Programmers will accept
    - Lightweight
  - Scales to large programs
  - Solves many different problems

Type Qualifiers

- Extend standard type systems (C, Java, ML)
  - Programmers already use types
  - Programmers understand types
  - Get programmers to write down a little more...

const int	ANSI C
ptr(tainted char)	Format-string vulnerabilities
kernel ptr(char) → char	User/kernel vulnerabilities

Application: Format String Vulnerabilities

- I/O functions in C use format strings

printf("Hello!");	Hello!
printf("Hello, %s!", name);	Hello, *name* !

- Instead of

  printf("%s", name);

  Why not

  printf(name); ?

Format String Attacks

- Adversary-controlled format specifier

  ```
  name := <data-from-network>
  printf(name);   /* Oops */
  ```

  - Attacker sets name = "%s%s%s" to crash program
  - Attacker sets name = "...%n..." to write to memory
    - Yields (often remote root) exploits
- Lots of these bugs in the wild
  - New ones weekly on bugtraq mailing list
  - Too restrictive to forbid variable format strings

Using Tainted and Untainted

- Add qualifier annotations

```
int printf(untainted char *fmt, ...)
tainted char *getenv(const char *)
```

tainted = may be controlled by adversary

untainted = must not be controlled by adversary

Subtyping

```
void f(tainted int);
untainted int a;
f(a);
```

OK

f accepts tainted or untainted data

untainted ≤ tainted

```
void g(untainted int);
tainted int b;
f(b);
```

Error

g accepts only untainted data

tainted ≰ untainted

untainted < tainted

Demo of cqual

http://www.cs.umd.edu/~jfoster

The Plan

- The Nice Theory
- The Icky Stuff in C
- Something Completely Different
  - (Not really)

A Simple Language

- We'll add type qualifiers to lambda calculus
  - …with a few extra constructs
  - Same approach works for other languages (like C)

e ::= x | n | true | false | if e then e else e
  | fun f (x:t):t = e | e e
t ::= int | bool | t → t

Type Qualifiers

- Let Q be the set of type qualifiers
  - Assumed to be chosen in advance and fixed
  - E.g., Q = {tainted, untainted}
- Then the *qualified types* are just
  - qt ::= int^{Q} | $bool^{Q}$ | qt $\to^{Q}$ qt

Abstract Syntax with Qualifiers

e ::= x | n | true | false | if e then e else e
  | fun f^{Q} (x:qt):qt = e | e e | annot(Q, e) | check(Q, e)

- annot(Q, e) = "expression e has qualifier Q"
  - Will sometimes write as superscript
- check(Q, e) = "fail if e does not have qualifier Q"
  - Checks only the top-level qualifier

- Examples:
  - fun fread (x:qt):$int^{tainted}$ = …$42^{tainted}$
  - fun printf (x:qt):qt' = check(untainted, x), …

Typing Rules: Qualifier Introduction

- Newly-constructed values have "bare" types

$$\frac{}{G \mid\!-\!- n : int}$$

$$\frac{}{G \mid\!-\!- true : bool} \qquad \frac{}{G \mid\!-\!- false : bool}$$

- Annotation adds an outermost qualifier

$$\frac{G \mid\!-\!- e1 : s}{G \mid\!-\!- annot(Q, e) : Q\ s}$$

Typing Rules: Qualifier Elimination

- By default, discard qualifier at destructors

$$\frac{G \mid\text{--}\ e1 : bool^{Q} \quad G \mid\text{--}\ e2 : qt \quad G \mid\text{--}\ e3 : qt}{G \mid\text{--}\ \text{if } e1 \text{ then } e2 \text{ else } e3 : qt}$$

- Use check() if you want to do a test

$$\frac{G \mid\text{--}\ e1 : Q\ s}{G \mid\text{--}\ check(Q, e) : Q\ s}$$

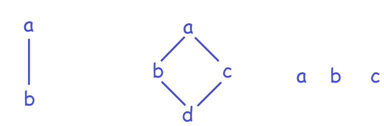
Subtyping

- Our example used *subtyping*
  - If anyone expecting a T can be given an S instead, then S is a *subtype* of T.
  - Allows untainted to be passed to tainted positions
  - I.e., check(tainted, annot(untainted, 42)) should typecheck
- How do we add that to our system?

Partial Orders

- Qualifiers Q come with a partial order $\leq$:
  - $q \leq q$ (reflexive)
  - $q \leq p, p \leq q \Rightarrow q = p$ (anti-symmetric)
  - $q \leq p, p \leq r \Rightarrow q \leq r$ (transitive)
- Qualifiers introduce subtyping
- In our example:
  - untainted < tainted

Example Partial Orders



2-point lattice

Discrete partial order

- Lower in picture = lower in partial order
- Edges show $\leq$ relations

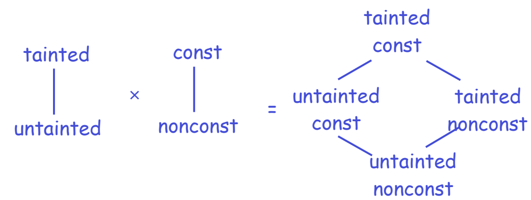
Combining Partial Orders

- Let $(Q_1, \leq_1)$ and $(Q_2, \leq_2)$ be partial orders
- We can form a new partial order, their cross-product:

$$(Q_1, \leq_1) \times (Q_2, \leq_2) = (Q, \leq)$$

where
  - $Q = Q_1 \times Q_2$
  - $(a, b) \leq (c, d)$ if $a \leq_1 c$ and $b \leq_2 d$

Example



- Makes sense with orthogonal sets of qualifiers
  - Allows us to write type rules assuming only one set of qualifiers

Extending the Qualifier Order to Types

$$\frac{Q \leq Q'}{bool^{Q} \leq bool^{Q'}} \qquad \frac{Q \leq Q'}{int^{Q} \leq int^{Q'}}$$

- Add one new rule *subsumption* to type system

$$\frac{G \mid\text{--}\ e : qt \quad qt \leq qt'}{G \mid\text{--}\ e : qt'}$$

- Means: If any position requires an expression of type qt', it is safe to provide it a subtype qt

Use of Subsumption

|-- 42 : int
—————————————————
|-- annot(untainted, 42) : untainted int   untainted ≤ tainted
—————————————————
|-- annot(untainted, 42) : tainted int
—————————————————
|-- check(tainted, annot(untainted, 42)) : tainted int

Subtyping on Function Types

- What about function types?

$$\frac{?}{qt1 \to^{Q} qt2 \le qt1' \to^{Q'} qt2'}$$

- Recall: S is a subtype of T if an S can be used anywhere a T is expected
  - When can we replace a call "f x" with a call "g x"?

Replacing "f x" by "g x"

- When is $\underbrace{qt1' \to^{Q'} qt2'}_{g} \le \underbrace{qt1 \to^{Q} qt2}_{f}$?
- Return type:
  - We are expecting qt2 (f's return type)
  - So we can only return *at most* qt2
  - $qt2' \le qt2$
- Example: A function that returns tainted can be replaced with one that returns untainted

Replacing "f x" by "g x" (cont'd)

- When is $\underbrace{qt1' \to^{Q'} qt2'}_{g} \le \underbrace{qt1 \to^{Q} qt2}_{f}$?
- Argument type:
  - We are supposed to accept qt1 (f's argument type)
  - So we must accept *at least* qt1
  - $qt1 \le qt1'$
- Example: A function that accepts untainted can be replaced with one that accepts tainted

Subtyping on Function Types

$$\frac{qt1' \le qt1 \quad qt2 \le qt2' \quad Q \le Q'}{qt1 \to^{Q} qt2 \le qt1' \to^{Q'} qt2'}$$

- We say that $\to$ is
  - *Covariant* in the range (subtyping dir the same)
  - *Contravariant* in the domain (subtyping dir flips)

Dynamic Semantics with Qualifiers

- Operational semantics tags values with qualifiers
  - $v ::= x \mid n^Q \mid true^Q \mid false^Q$
    $\mid fun\ f^Q\ (x : qt1) : qt2 = e$
- Evaluation rules same as usual, carrying the qualifiers along, e.g.,

$$\frac{}{\text{if true}^Q \text{ then e1 else e2} \rightarrow \text{e1}}$$

Dynamic Semantics with Qualifiers (cont'd)

- One new rule checks a qualifier:

$$\frac{Q' \leq Q}{\text{check}(Q, v^{Q'}) \rightarrow v}$$

  - Evaluation at a check can continue only if the qualifier matches what is expected
    - Otherwise the program gets *stuck*
  - (Also need rule to evaluate under a check)

Soundness

- We want to prove
  - Preservation: Evaluation preserves types
  - Progress: Well-typed programs don't get stuck
- Proof: Exercise
  - See if you can adapt standard proofs to this system
  - (Not too much work; really just need to show that check doesn't get stuck)

Updateable References

- Our language is missing *side-effects*
  - There's no way to write to memory
  - Recall that this doesn't limit expressiveness
    - But side-effects sure are handy

Language Extension

- We'll add ML-style references
  - e ::= … | ref^{Q} e | !e | e := e
    - ref^{Q} e -- Allocate memory and set its contents to e
      - Returns memory location
      - Q is qualifier on pointer (not on contents)
    - !e -- Return the contents of memory location e
    - e1 := e2 -- Update e1's contents to contain e2
  - Things to notice
    - No null pointers (memory always initialized)
    - No mutable local variables (only pointers to heap allowed)

Static Semantics

- Extend type language with references:
  - qt ::= … | ref^{Q} qt
    - Note: In ML the ref appears on the right

$$\frac{G \mid\text{-- } e : qt}{G \mid\text{-- } ref^{Q}\ e : ref^{Q}\ qt}$$

$$\frac{G \mid\text{-- } e : ref^{Q}\ qt}{G \mid\text{-- } !e : qt} \qquad \frac{G \mid\text{-- } e1 : ref^{Q}\ qt \quad G \mid\text{-- } e2 : qt}{G \mid\text{-- } e1 := e2 : qt}$$

Subtyping References

- The *wrong* rule for subtyping references is

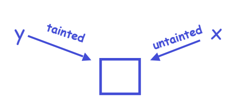
$$\frac{Q \le Q' \quad qt \le qt'}{ref^{Q}\ qt \le ref^{Q'}\ qt'}$$

- Counterexample

let x = ref 0^{untainted} in
  let y = x in
    y := 3^{tainted};
    check(untainted, !x)   oops!

You've Got Aliasing!

- We have multiple names for the same memory location
  - But they have different types
  - *And* we can **write** into memory at different types



Solution #1: Java's Approach

- Java uses this subtyping rule
  - If S is a subclass of T, then S[] is a subclass of T[]
- Counterexample:
  - Foo[] a = new Foo[5];
  - Object[] b = a;
  - b[0] = new Object(); // forbidden at runtime
  - a[0].foo(); // …so this can't happen

Solution #2: Purely Static Approach

- Reason from rules for functions
  - A reference is like an object with two methods:
    - get : unit → qt
    - set : qt → unit
  - Notice that qt occurs both co- and contravariantly
- The right rule:

$$\frac{Q \leq Q' \quad qt \leq qt' \quad qt' \leq qt}{ref^{Q}\ qt \leq ref^{Q'}\ qt'} \quad \text{or} \quad \frac{Q \leq Q' \quad qt = qt'}{ref^{Q}\ qt \leq ref^{Q'}\ qt'}$$

Soundness

- We want to prove
  - Preservation: Evaluation preserves types
  - Progress: Well-typed programs don't get stuck
- Can you prove it with updateable references?
  - Hint: You'll need a stronger induction hypothesis
    - You'll need to reason about types in the store
      - E.g., so that if you retrieve a value out of the store, you know what type it has

Type Qualifier Inference

- Recall our motivating example
  - We gave a legacy C program that had *no information* about qualifiers
  - We added signatures *only* for the standard library functions
  - Then we checked whether there were any contradictions
- This requires *type qualifier inference*

Type Qualifier Inference Statement

- Given a program with
  - Qualifier annotations
  - Some qualifier checks
  - And no other information about qualifiers
- Does there exist a valid typing of the program?

- We want an algorithm to solve this problem

First Problem: Subsumption Rule

$$\frac{G \mid\text{--}\ e : qt \quad qt \leq qt'}{G \mid\text{--}\ e : qt'}$$

- We're allowed to apply this rule at any time
  - Makes it hard to develop a deterministic algorithm
  - Type checking is not *syntax driven*
- Fortunately, we don't have that many choices
  - For each expression e, we need to decide
    - Do we apply the "regular" rule for e?
    - Or do we apply subsumption (how many times)?

Getting Rid of Subsumption

- Lemma: Multiple sequential uses of subsumption can be collapsed into a single use
  - Proof: Transitivity of ≤

- So now we need only apply subsumption once after each expression

Getting Rid of Subsumption (cont'd)

- We can get rid of the separate subsumption rule

$$\frac{G \mid\text{--}\ e1 : qt' \to^{Q} qt'' \quad G \mid\text{--}\ e2 : qt \quad qt \leq qt'}{G \mid\text{--}\ e1\ e2 : qt''}$$

$$\frac{G \mid\text{--}\ e : Q'\ s \quad Q' \leq Q}{G \mid\text{--}\ check(Q, e) : Q\ s}$$

- Apply the same reasoning to the other rules
  - We're left with a purely syntax-directed system

Second Problem: Assumptions

- Let's take a look at the rule for functions:

$$\frac{G,\ f: qt1 \rightarrow^{Q} qt2,\ x{:}qt1 \mid\text{--}\ e : qt2' \quad qt2' \leq qt2}{G \mid\text{--}\ \text{fun } f^{Q}\ (x{:}qt1){:}qt2 = e : qt1 \rightarrow^{Q} qt2}$$

- There's a problem with applying this rule
  - We're assuming that we're given the argument type qt1 and the result type qt2
  - But in the problem statement, we said we only have annotations and checks

Type Checking vs. Type Inference

- Let's think about C's type system
  - C requires programmers to annotate function types
  - …but not other places
    - E.g., when you write down 3 + 4, you don't need to give that a type
  - So all type systems trade off programmer annotations vs. computed information
- Type checking = it's "obvious" how to check
- Type inference = it's "more work" to check

Why Do We Want Qualifier Inference?

- Because our programs weren't written with qualifiers in mind
  - They don't have qualifiers in their type annotations
  - In particular, functions don't list qualifiers for their arguments
- Because it's less work for the programmer
  - …but it's harder to understand when a program doesn't type check

Adding Fresh Qualifiers

- We'll add qualifier variables a, b, c, … to our set of qualifiers
  - (Letters closer to p, q, r will stand for constants)
- Define fresh : t → qt as
  - $fresh(int) = int^{a}$
  - $fresh(bool) = bool^{a}$
  - $fresh(ref^{Q}\ t) = ref^{a}\ fresh(t)$
  - $fresh(t1 \rightarrow t2) = fresh(t1) \rightarrow^{a} fresh(t2)$
    - Where a is fresh

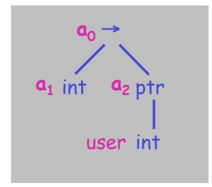
Rule for Functions

$$\frac{qt1 = \text{fresh}(t1) \quad qt2 = \text{fresh}(t2) \qquad G, f: qt1 \to^{Q} qt2, x{:}qt1 \;|\text{--}\; e : qt2' \quad qt2' \leq qt2}{G \;|\text{--}\; \text{fun } f^{Q}\ (x{:}t1){:}t2 = e : qt1 \to^{Q} qt2}$$

A Picture of Fresh Qualifiers

ptr(tainted char)

int → user ptr(int)



Where Are We?

- A syntax-directed system
  - For each expression, clear which rule to apply
- Constant qualifiers
- Variable qualifiers
  - Want to find a valid assignment to constant qualifiers
- Constraints $qt \leq qt'$ and $Q \leq Q'$
  - These restrict our use of qualifiers
  - These will limit solutions for qualifier variables

Qualifier Inference Algorithm

1. Apply syntax-directed type inference rules
   - This generates fresh unknowns and constraints among the unknowns
2. Solve the constraints
   - Either compute a *solution*
   - Or fail, if there is no solution
     - Implies the program has a type error
     - Implies the program *may* have a bug

Solving Constraints: Step 1

- Constraints of the form qt ≤ qt' and Q ≤ Q'
  - qt ::= int^Q | bool^Q | qt $\rightarrow^Q$ qt | ref^Q qt
- Solve by simplifying
  - Can read solution off of simplified constraints
- We'll present algorithm as a rewrite system
  - S ==> S' means constraints S rewrite to (simpler) constraints S'

Solving Constraints: Step 1

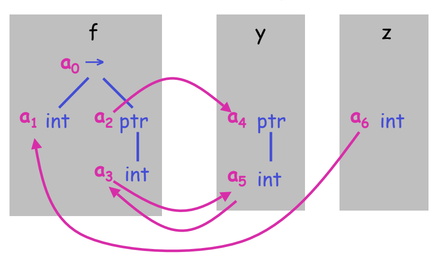
- S + { int^Q ≤ int$^{Q'}$ } ==> S + { Q ≤ Q' }
- S + { bool^Q ≤ bool$^{Q'}$ } ==> S + { Q ≤ Q' }
- S + { qt1 $\rightarrow^Q$ qt2 ≤ qt1' $\rightarrow^{Q'}$ qt2' } ==>
  S + { qt1' ≤ qt1 } + { qt2 ≤ qt2' } + { Q ≤ Q' }
- S + { ref^Q qt1 ≤ ref$^{Q'}$ qt2 } ==>
  S + { qt1 ≤ qt2 } + { qt2 ≤ qt1 } + { Q ≤ Q' }
- S + { mismatched constructors } ==> error
  - Can't happen if program correct w.r.t. std types

Solving Constraints: Step 2

- Our type system is called a *structural subtyping system*
  - If qt ≤ qt', then qt and qt' have the same shape
- When we're done with step 1, we're left with constraints of the form Q ≤ Q'
  - Where either of Q, Q' may be an unknown
  - This is called an *atomic subtyping system*
  - That's because qualifiers don't have any "structure"

Constraint Generation

ptr(int) f(x : int) = { ... }   y := f(z)

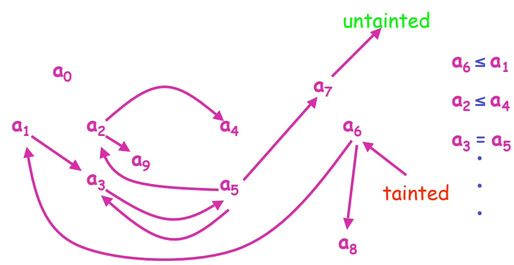


$a_6 \leq a_1$

$a_2 \leq a_4$

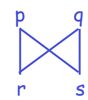
$a_3 = a_5$

Constraints as Graphs



Some Bad News

- Solving atomic subtyping constraints is NP-hard in the general case
- The problem comes up with some really weird partial orders



But That's OK

- These partial orders don't seem to come up in practice
  - Not very natural
- Most qualifier partial orders have one of two desirable properties:
  - They either always have *least upper bounds* or *greatest lower bounds* for any pair of qualifiers

Lubs and Glbs

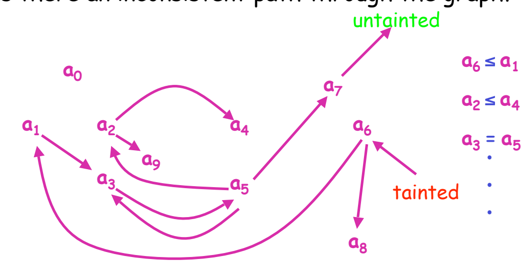
- lub = Least upper bound
  - p lub q = r such that
    - $p \leq r$ and $q \leq r$
    - If $p \leq s$ and $q \leq s$, then $r \leq s$
- glb = Greatest lower bound, defined dually
- lub and glb may not exist

Lattices

- A *lattice* is a partial order such that lubs and glbs always exist
- If Q is a lattice, it turns out we can use a really simple algorithm to check satisfiability of constraints over Q

Satisfiability via Graph Reachability

Is there an inconsistent path through the graph?



Satisfiability via Graph Reachability

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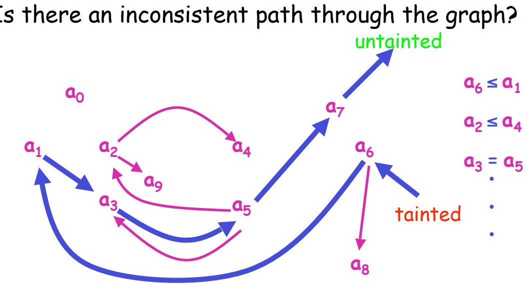
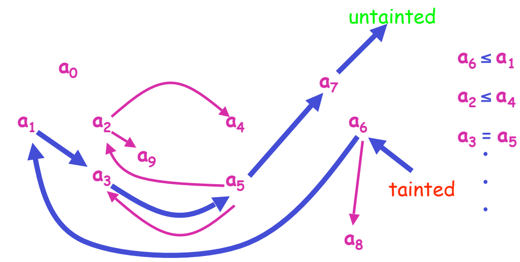


Satisfiability via Graph Reachability

tainted $\leq a_6 \leq a_1 \leq a_3 \leq a_5 \leq a_7 \leq$ untainted



Satisfiability in Linear Time

- Initial program of size n
  - Fixed set of qualifiers tainted, untainted, ...
- Constraint generation yields O(n) constraints
  - Recursive abstract syntax tree walk
- Graph reachability takes O(n) time
  - Works for semi-lattices, discrete p.o., products

Limitations of Subtyping

- Subtyping gives us a kind of *polymorphism*
  - A *polymorphic* type represents multiple types
  - In a subtyping system, qt represents qt and all of qt's subtypes
- As we saw, this flexibility helps make the analysis more precise
  - But it isn't always enough…

Limitations of Subtype Polymorphism

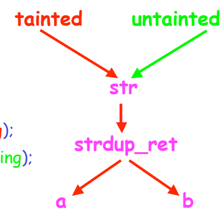
- Consider tainted and untainted again
  - untainted ≤ tainted
- Let's look at the identity function
  - fun id (x:int):int = x
- What qualified types can we infer for id?

Types for id

- fun id (x:int):int = x
  - tainted int → tainted int
    - Fine but untainted data passed in becomes tainted
  - untainted int → untainted int
    - Fine but can't pass in tainted data
  - untainted int → tainted int
    - Not too useful
  - tainted int → untainted int
    - Impossible

Function Calls and Context-Sensitivity

```
char *strdup(char *str) {
   // return a copy of str
}
char *a = strdup(tainted_string);
char *b = strdup(untainted_string);
```



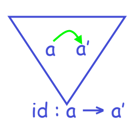
- All calls to strdup conflated
  - *Monomorphic* or *context-insensitive*

What's Happening Here?

- The qualifier on x appears both covariantly and contravariantly in the type
  - We're stuck
- We need *parametric polymorphism*
  - Consider fun id (x:int):int = x

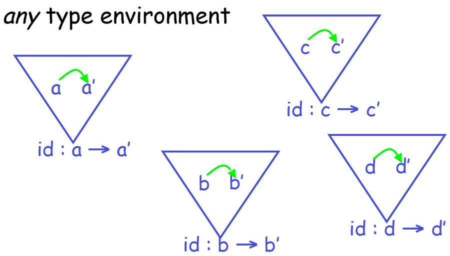
The Observation of Parametric Polymorphism

- Type inference on id yields a proof like this:



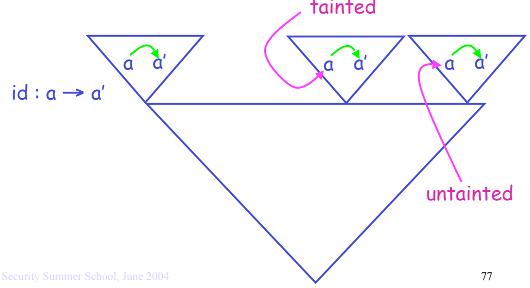
The Observation of Parametric Polymorphism

- We can duplicate this proof *for any* a,a', *in any* type environment



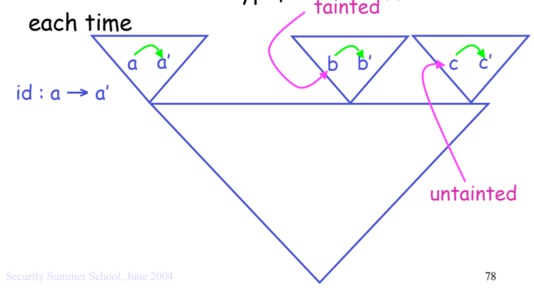
The Observation of Parametric Polymorphism

- Thus when we use id…



The Observation of Parametric Polymorphism

- We can "inline" its type, with a different a each time



Polymorphically Constrained Types

- Notice that we inlined not only the *type* (as in ML), but also the *constraints*
- We need polymorphically constrained types

  x : ∀**a**.qt where *C*

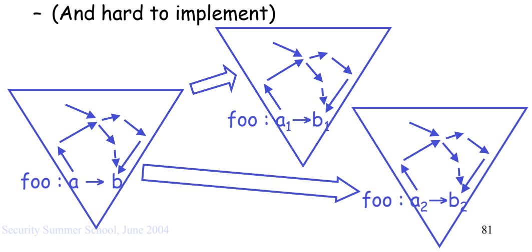
  - For any qualifiers **a** where constraints *C* hold, x has type qt

Examples of Polymorphically Constrained Types

- int id(int x) { return x; }
  - id : ∀a,b. a int → b int where a ≤ b
- char *strcat(char *s, char *append);
  - strcat : ∀a,b,c. (a char * x b char *) → c char * where b ≤ c, a = c
- void *malloc(size_t size);
  - malloc : ∀a. () → a void * where []

Polymorphically Constrainted Types

- Must copy constraints at each instantiation
  - Looks inefficient
  - (And hard to implement)



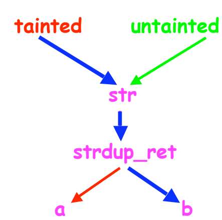
Comparison to Type Polymorphism

- ML-style polymorphic type inference is EXPTIME-hard
  - In practice, it's fine
  - Bad case can't happen here, because we're polymorphic *only* in the qualifiers
    - That's because we'll apply this to C

A Better Solution: CFL Reachability

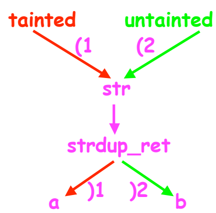
- Can reduce this to another problem
  - Equivalent to the constraint-copying formulation
  - Supports polymorphic recursion in qualifiers
  - It's easy to implement
  - It's efficient: $O(n^3)$
    - Previous best algorithm $O(n^8)$ [Mossin, PhD thesis]
- Idea due to Horwitz, Reps, and Sagiv [POPL'95], and Rehof, Fahndrich, and Das [POPL'01]

The Problem Restated: Unrealizable Paths



- No execution can exhibit that particular call/return sequence

Only Propagate Along Realizable Paths



- Add edge labels for calls and returns
  - Only propagate along *valid* paths whose returns balance calls

Type Rule for Instantiation

- Now when we mention the name of a function, we'll instantiate it using the following rule

$$\frac{qt = G(f) \quad qt' = \mathrm{fresh}(qt) \quad qt \xrightarrow{)_i} qt'}{G \mid\!-\!- f_i : qt'}$$

Rules for Propagating Parenthesis Edges

- $S + \{ \mathrm{int}^Q \xrightarrow{)i} \mathrm{int}^{Q'} \} \Longrightarrow S + \{ Q \xrightarrow{)i} Q' \}$
- $S + \{ \mathrm{int}^Q \xrightarrow{(i} \mathrm{int}^{Q'} \} \Longrightarrow S + \{ Q \xrightarrow{(i} Q' \}$

Rules for Propagating Parenthesis Edges

- $S + \{ qt1 \rightarrow^{Q} qt2 \quad \xrightarrow{)i} \quad qt1' \rightarrow^{Q'} qt2' \} \Longrightarrow$

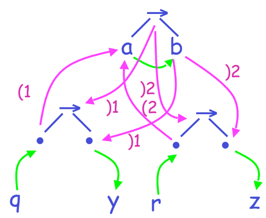
  $S + \{ qt1' \xrightarrow{(i} qt1 \} + \; \{ qt2 \xrightarrow{)i} qt2' \} + \ldots$

- $S + \{ qt1 \rightarrow^{Q} qt2 \quad \xrightarrow{(i} \quad qt1' \rightarrow^{Q'} qt2' \} \Longrightarrow$

  $S + \{ qt1' \xrightarrow{)i} qt1 \} + \; \{ qt2 \xrightarrow{(i} qt2' \} + \ldots$

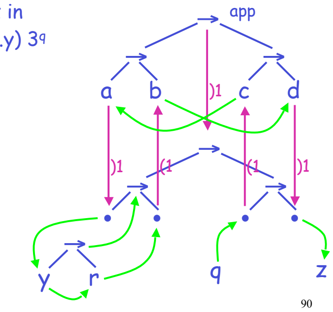
A Simple Example

fun id x = x in
let y = id_1 3^q
let z = id_2 4^r



A Higher-Order Example

fun app f x = f x in
let z = app_1 (\y.y) 3^q



Two Observations

- We *are* doing constraint copying
  - Notice the edge from c to a got "copied" to q to y
    - We didn't draw the transitive edge, but we could have
- This algorithm can be made demand-driven
  - We only need to worry about paths from constant qualifiers
  - Good implications for scalability in practice

CFL Reachability

- We're trying to find paths through the graph whose edges are a language in some grammar
  - Called the *CFL Reachability* problem
  - Computable in cubic time

Grammar for Matched Paths

M ::= (i M)i	for any i
| M M	
| d	regular subtyping edge
|	empty

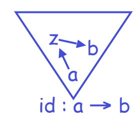
- Also can include other paths, depending on application

Global Variables

- Consider the following identity function

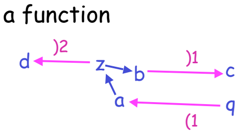
  fun id(x:int):int = z := x; !z

  - Here z is a global variable
- Typing of id, roughly speaking:



Global Variables

- Suppose we instantiate and apply id to q inside of a function

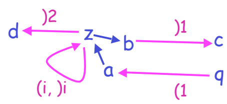


  - And then another function returns z
  - Uh oh! (1)2 is not a valid flow path
    - But q may certainly reach d

Thou Shalt Not Quantify a Global Type (Qualifier) Variable

- We violated a basic rule of polymorphism
  - We generalized a variable free in the environment
  - In effect, we duplicated z at each instantiation
- Solution: Don't do that!

Our Example Again



- We want anything flowing into z, on any path, to flow out in any way
  - Add a self-loop to z that consumes any mismatched parens

Typing Rules, Fixed

- Track unquantifiable vars at generalization

$$\frac{qt1 = \mathrm{fresh}(t1) \quad qt2 = \mathrm{fresh}(t2) \qquad G,\ f\!: (qt1 \to^{Q} qt2,\ v),\ x\!:\!qt1 \mid\!\!-\!\!-\ e : qt2' \quad qt2' \le qt2 \qquad v = \text{free vars of } G}{G \mid\!\!-\!\!-\ \mathrm{fun}\ f^{Q}\ (x\!:\!t1)\!:\!t2 = e : (qt1 \to^{Q} qt2,\ v)}$$

Typing Rules, Fixed

- Add self-loops at instantiation

$$\frac{(qt,\ v) = G(f) \quad qt' = \mathrm{fresh}(qt) \quad qt \xrightarrow{)_i} qt' \qquad v \xrightarrow{)_i} v \qquad v \xrightarrow{(_i} v}{G \mid\!\!-\!\!-\ f_i : qt'}$$

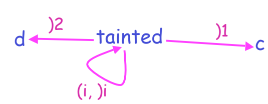
Qualifier Constants

- Also use self-loops for qualifier constants

let taint () = tainted 42 in

let c = taint()

let d = taint()



Efficiency

- Constraint generation yields O(n) constraints
  - Same as before
  - Important for scalability
- Context-free language reachability is $O(n^3)$
  - But a few tricks make it practical (not much slowdown in analysis times)
- For more details, see
  - Rehof + Fahndrich, POPL'01

Type Qualifiers: The Icky Stuff in C

Introduction

- That's all the theory behind this system
  - More complicated system: flow-sensitive qualifiers
  - Not going to cover that here
- Suppose we want to apply this to a language like C
  - It's a little more complicated!

Local Variables in C

- The first (easiest) problem: C doesn't use ref
  - It has malloc for memory on the heap
  - But local variables on the stack are also updateable:

```
void foo(int x) {
  int y;
  y = x + 3;
  y++;
  x = 42;
}
```

- The C types aren't quite enough
  - 3 : int, but can't update 3!

L-Types and R-Types

- C hides important information:
  - Variables behave different in l- and r-positions
    - l = left-hand-side of assignment, r = rhs
  - On lhs of assignment, x refers to *location* x
  - On rhs of assignment, x refers to *contents of location* x

Mapping to ML-Style References

- Variables will have ref types:
  - x : ref^{Q} <contents type>
  - Parameters as well, but r-types in fn sigs
- On rhs of assignment, add deref of variables
  - Address-of uses ref type directly

```
void foo(int x) {          foo (x:int):void =
                             let x = ref x in
  int y;                     let y = ref 0 in
  y = x + 3;                   y := (!x) + 3;
  y++;                         y := (!y) + 1;
  x = 42;                      x := 42;
  g(&y);                       g(y)
}
```


Multiple Files

- Most applications have multiple source code files
- If we do inference on one file without the others, won't get complete information:

```
extern int t;

x = t;
```

```
$tainted int t = 0;
```

  - Problem: In left file, we're assuming t may have any qualifier (we make a fresh variable)

Multiple Files: Solution #1

- Don't analyze programs with multiple files!
- Can use CIL merger from Necula to turn a multi-file app into a single-file app
  - E.g., I have a merged version of the linux kernel, 470432 lines
- Problem: Want to present results to user
  - Hard to map information back to original source

Multiple Files: Solution #2

- Make conservative assumptions about missing files
  - E.g., anything globally exposed may be tainted
- Problem: Very conservative
  - Going to be hard to infer useful types

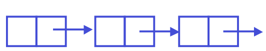
Multiple Files: Solution #3

- Give tool all files at same time
  - Whole-program analysis
- Include files that give types to library functions
  - In CQual, we have prelude.cq
- Unify (or just equate) types of globals
- Problem: Analysis really needs to scale

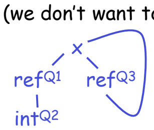
Structures (or Records): Scalability Issues

- One problem: Recursion
  - Do we allow qualifiers on different levels to differ?

```
struct list {
    int elt;
    struct list *next;
}
```



  - Our choice: no (we don't want to do shape analysis)



Structures: Scalability Issues

- Natural design point: All instances of the same struct share the same qualifiers
- This is what we used to do
  - Worked pretty well, especially for format-string vulnerabilities
  - Scales well to large programs (linear in program size)
- Fell down for user/kernel pointers
  - Not precise enough

Structures: Scalability Issues

- Second problem: Multiple Instances
  - Naïvely, each time we see

    `struct inode x;`

    we'd like to make a copy of the type struct inode with fresh qualifiers
  - Structure types in C programs are often long
    - struct inode in the Linux kernel has 41 fields!
    - Often contain lots of nested structs
  - This won't scale!

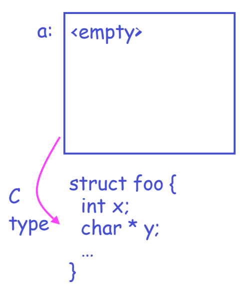
Multiple Structure Instances

- Instantiate struct types lazily
  - When we see

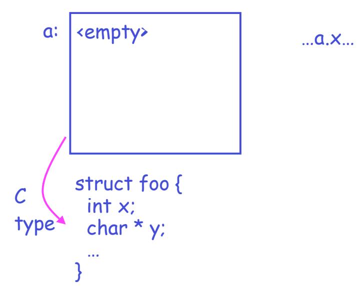
    `struct inode x;`

    we make an empty record type for x with a pointer to type struct inode
  - Each time we access a field f of x, we add fresh qualifiers for f to x's type (if not already there)
  - When two instances of the same struct meet, we unify their records
    - This is a heuristic we've found is acceptable

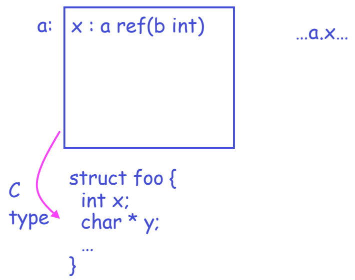
Lazy Field Expansion



Lazy Field Expansion



Lazy Field Expansion



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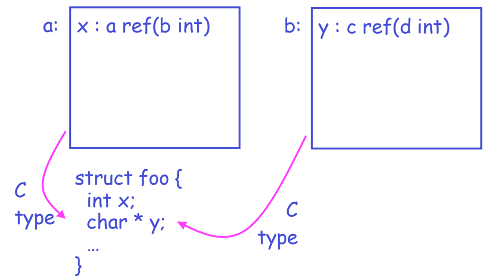
Lazy Field Expansion



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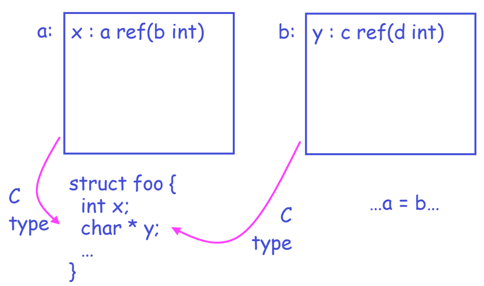
Lazy Field Expansion



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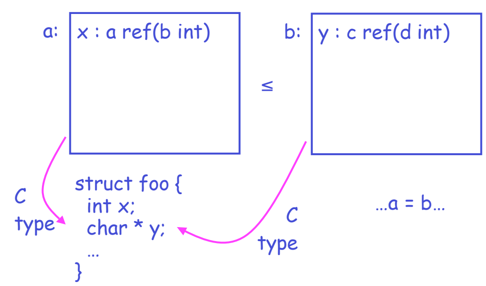
Lazy Field Expansion



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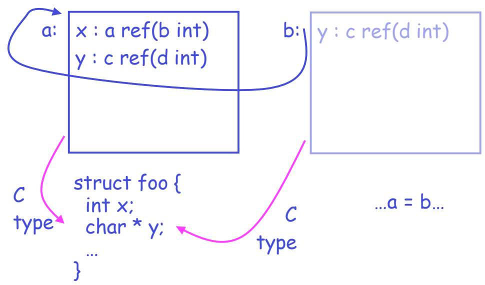
Lazy Field Expansion



Subtyping Under Pointer Types

- Recall we argued that an updateable reference behaves like an object with get and set operations
- Results in this rule:

$$\frac{Q \le Q' \quad qt \le qt' \quad qt' \le qt}{ref^{Q}\ qt \le ref^{Q'}\ qt'}$$

- What if we can't write through reference?

Subtyping Under Pointer Types

- C has a type qualifier const
  - If you declare const int *x, then *x = ... not allowed
- So const pointers don't have "get" method
  - Can treat ref as covariant

$$\frac{Q \le Q' \quad qt \le qt' \quad const \le Q'}{ref^{Q}\ qt \le ref^{Q'}\ qt'}$$

Subtyping Under Pointer Types

- Turns out this is very useful
  - We're tracking taintedness of strings
  - Many functions read strings without changing their contents
  - Lots of use of const + opportunity to add it

Presenting Inference Results

- Type error = unsatisfiable constraints
  - E.g., path from tainted to untainted
- Heuristics for presenting "good" errors
  - Suppress derivative errors
    - L ≤ l1 ≤ … ≤ ln ≤ x ≤ u1 ≤ … ≤ um ≤ u where li = uj
  - Suppress redundant errors
    - Only report one error for the above path
  - Suppress purely anonymous paths
    - Those that correspond to intermediate qualifier variables

Type Casts

Experiment: Format String Vulnerabilities

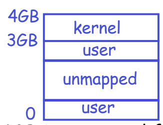
- Analyzed 10 popular unix daemon programs
  - Annotations shared across applications
    - One annotated header file for standard libraries
    - Includes annotations for polymorphism
      - Critical to practical usability
- Found several known vulnerabilities
  - Including ones we didn't know about
- User interface critical

Results: Format String Vulnerabilities

Name	Warn	Bugs
identd-1.0.0	0	0
mingetty-0.9.4	0	0
bftpd-1.0.11	1	1
muh-2.05d	2	~2
cfengine-1.5.4	5	3
imapd-4.7c	0	0
ipopd-4.7c	0	0
mars_nwe-0.99	0	0
apache-1.3.12	0	0
openssh-2.3.0p1	0	0

Experiment: User/kernel Vulnerabilities (Johnson + Wagner 04)

- In the Linux kernel, the kernel and user/mode programs share address space



  - The top 1GB is reserved for the kernel
  - When the kernel runs, it doesn't need to change VM mappings
    - Just enable access to top 1GB
    - When kernel returns, prevent access to top 1GB

Tradeoffs of This Memory Model

- Pros:
  - Not a lot of overhead
  - Kernel has direct access to user space
- Cons:
  - Leaves the door open to attacks from untrusted users
  - A pain for programmers to put in checks

An Attack

- Suppose we add two new system calls

```
int x;
void sys_setint(int *p) { memcpy(&x, p, sizeof(x)); }
void sys_getint(int *p) { memcpy(p, &x, sizeof(x)); }
```

- Suppose a user calls getint(buf)
  - Well-behaved program: buf points to user space
  - Malicious program: buf points to unmapped memory
  - Malicious program: buf points to kernel memory
    - We've just written to kernel space! Oops!

Another Attack

- Can we compromise security with setint(buf)?
  - What if buf points to private kernel data?
    - E.g., file buffers
  - Result can be read with getint

The Solution: copy_from_user, copy_to_user

- Our example should be written

```
int x;
void sys_setint(int *p) { copy_from_user(&x, p, sizeof(x)); }
void sys_getint(int *p) { copy_to_user(p, &x, sizeof(x)); }
```

- These perform the required safety checks
  - Return number of bytes that couldn't be copied
  - from_user pads destination with 0's if couldn't copy

It's Easy to Forget These

- Pointers to kernel and user space look the same
  - That's part of the point of the design
- Linux 2.4.20 has 129 syscalls with pointers to user space
  - All 129 of those need to use copy_from/to
  - The ioctl implementation passes user pointers to device drivers (without sanitizing them first)
- The result: Hundreds of copy_from/_to
  - One (small) kernel version: 389 from, 428 to
  - And there's no checking

User/Kernel Type Qualifiers

- We can use type qualifiers to distinguish the two kinds of pointers
  - kernel -- This pointer is under kernel control
  - user -- This pointer is under user control
- Subtyping kernel < user
  - It turns out copy_from/copy_to can accept pointers to kernel space where they expect pointers to user space

Type Signatures

- We add signatures for the appropriate fns:

```
int copy_from_user(void *kernel to,
                   void *user from, int len)
int memcpy(void *kernel to,
           void *kernel from, int len)
int x;
void sys_setint(int *user p) {
  copy_from_user(&x, p, sizeof(x)); }
void sys_getint(int *user p) {
  memcpy(p, &x, sizeof(x)); }
```

Lives in kernel

OK

OK

Error

Qualifiers and Type Structure

- Consider the following example:

```
void ioctl(void *user arg) {
  struct cmd { char *datap; } c;
  copy_from_user(&c, arg, sizeof(c));
  c.datap[0] = 0;    // not a good idea
}
```

- The pointer arg comes from the user
  - So datap in c also comes from the user
  - We shouldn't deference it without a check

Well-Formedness Constraints

- Simpler example

  char **user p;
    - Pointer p is under user control
    - Therefore so is *p
- We want a rule like:
  - In type ref^{user} (Q s), it must be that Q ≤ user
  - This is a *well-formedness* condition on types

Well-Formedness Constraints

- As a type rule

$$\frac{\text{|--wf } (Q'\ s) \qquad Q' \leq Q}{\text{|--wf } ref^{Q}\ (Q'\ s)}$$

  - We implicitly require all types to be well-formed
- But what about other qualifiers?
  - Not all qualifiers have these structural constraints
  - Or maybe other quals want Q ≤ Q'

Well-Formedness Constraints

- Use conditional constraints

$$\frac{\text{|--wf } (Q'\ s) \qquad Q \leq user \Longrightarrow Q' \leq user}{\text{|--wf } ref^{Q}\ (Q'\ s)}$$

  - "If Q must be user, then Q' must be also"
- Specify on a per-qualifier level whether to generate this constraint
  - Not hard to add to constraint resolution

Well-Formedness Constraints

- Similar constraints for struct types

$$\frac{\text{For all } i,\ \vdash_{wf} (Q_i\ s_i) \qquad Q \le user \implies Q_i \le user}{\vdash_{wf} struct^Q (Q_1\ s_1, \ldots, Q_n\ s_n)}$$

  - Again, can specify this per-qualifier

A Tricky Example

```
int copy_from_user(<kernel>, <user>, <size>);
int i2cdev_ioctl(struct inode *inode, struct file *file, unsigned cmd,
                 unsigned long arg) {
  ...case I2C_RDWR:
      if (copy_from_user(&rdwr_arg,
                         (struct i2c_rdwr_iotcl_data *) arg,
                         sizeof(rdwr_arg)))
        return -EFAULT;
      for (i = 0; i < rdwr_arg.nmsgs; i++) {
        if (copy_from_user(rdwr_pa[i].buf,
                           rdwr_arg.msgs[i].buf,
                           rdwr_pa[i].len)) {
            res = -EFAULT; break;
  }}
```


A Tricky Example

```
int copy_from_user(<kernel>, <user>, <size>);
int i2cdev_ioctl(struct inode *inode, struct file *file, unsigned cmd,
                 unsigned long arg) {          [user]
  ...case I2C_RDWR:
      if (copy_from_user(&rdwr_arg,
                         (struct i2c_rdwr_iotcl_data *) arg,
                         sizeof(rdwr_arg)))
        return -EFAULT;
      for (i = 0; i < rdwr_arg.nmsgs; i++) {
        if (copy_from_user(rdwr_pa[i].buf,
                           rdwr_arg.msgs[i].buf,
                           rdwr_pa[i].len)) {
            res = -EFAULT; break;
  }}
```


A Tricky Example

```
int copy_from_user(<kernel>, <user>, <size>);
int i2cdev_ioctl(struct inode *inode, struct file *file, unsigned cmd,
                 unsigned long arg) {          [user]   [OK]
  ...case I2C_RDWR:
      if (copy_from_user(&rdwr_arg,
                         (struct i2c_rdwr_iotcl_data *) arg,
                         sizeof(rdwr_arg)))
        return -EFAULT;
      for (i = 0; i < rdwr_arg.nmsgs; i++) {
        if (copy_from_user(rdwr_pa[i].buf,
                           rdwr_arg.msgs[i].buf,
                           rdwr_pa[i].len)) {
            res = -EFAULT; break;
  }}
```

A Tricky Example

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  ...case I2C_RDWR:
      if (copy_from_user(&rdwr_arg,
                         (struct i2c_rdwr_iotcl_data *) arg,
                         sizeof(rdwr_arg)))
        return -EFAULT;
      for (i = 0; i < rdwr_arg.nmsgs; i++) {
        if (copy_from_user(rdwr_pa[i].buf,
                           rdwr_arg.msgs[i].buf,
                           rdwr_pa[i].len)) {
              res = -EFAULT; break;
} }
```

user (annotation on `unsigned long arg`)

OK (annotation on `arg`)

Bad (annotation on `rdwr_arg.msgs[i]`)

Experimental Results

- Ran on two Linux kernels
  - 2.4.20 -- 11 bugs found
  - 2.4.23 -- 10 bugs found
- Needed to add 245 annotations
  - Copy_from/to, kmalloc, kfree, …
  - All Linux syscalls take user args (221 calls)
    - Could have be done automagically (All begin with sys_)
- Ran both single file (unsound) and whole-kernel
  - Disabled subtyping for single file analysis

More Detailed Results

- 2.4.20, full config, single file
  - 512 raw warnings, 275 unique, 7 exploitable bugs
    - Unique = combine msgs for user qual from same line
- 2.4.23, full config, single file
  - 571 raw warnings, 264 unique, 6 exploitable bugs
- 2.4.23, default config, single file
  - 171 raw warnings, 76 unique, 1 exploitable bug
- 2.4.23, default config, whole kernel
  - 227 raw warnings, 53 unique, 4 exploitable bugs

Observations

- Quite a few false positives
  - Large code base magnifies false positive rate
- Several bugs persisted through a few kernels
  - 8 bugs found in 2.4.23 that persisted to 2.5.63
  - An unsound tool, MECA, found 2 of 8 bugs
  - ==> Soundness matters!

Observations

- Of 11 bugs in 2.4.23…
  - 9 are in device drivers
  - Good place to look for bugs!
  - Note: errors found in "core" device drivers
    - (4 bugs in PCMCIA subsystem)
- Lots of churn between kernel versions
  - Between 2.4.20 and 2.4.23
    - 7 bugs fixed
    - 5 more introduced

Conclusion

- Type qualifiers are specifications that…
  - Programmers will accept
    - Lightweight
  - Scale to large programs
  - Solve many different problems
- In the works: ccqual, jqual, Eclipse interface