

## Security via Type Qualifiers

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## Introduction

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- Ensuring that software is secure is hard
- Standard practice for software quality:
  - Testing
    - Make sure program runs correctly on set of inputs
  - Code auditing
    - Convince yourself and others that your code is correct

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## Drawbacks to Standard Approaches

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- Difficult
- Expensive
- Incomplete
- A **malicious adversary** is trying to exploit anything you miss!

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## Tools for Security

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- What more can we do?
  - Build tools that analyze source code
    - 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 security

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## 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

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## 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
```

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## 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);           ?
```

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## 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

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## Using Tainted and Untainted

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- 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

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## Subtyping

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

OK

f accepts **tainted** or  
**untainted** data

**untainted**  $\leq$  **tainted**

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

Error

g accepts only **untainted**  
data

**tainted**  $\not\leq$  **untainted**

**untainted**  $<$  **tainted**

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## Demo of cqual

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

## The Plan

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- The Nice Theory
- Polymorphism
- The Icky Stuff in C

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## Type Qualifiers for MinML

- We'll add type qualifiers to MinML
  - Same approach works for other languages (like C)
- Standard type systems define types as
  - $t ::= c0(t, \dots, t) \mid \dots \mid cn(t, \dots, t)$ 
    - Where  $\Sigma = c0 \dots cn$  is a set of *type constructors*
- Recall the **types** of MinML
  - $t ::= \text{int} \mid \text{bool} \mid t \rightarrow t$ 
    - Here  $\Sigma = \text{int}, \text{bool}, \rightarrow$  (written infix)

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## Type Qualifiers for MinML (cont'd)

- Let  $Q$  be the set of type qualifiers
  - Assumed to be chosen in advance and fixed
  - E.g.,  $Q = \{\text{tainted}, \text{untainted}\}$
- Then the *qualified types* are just
  - $qt ::= Q\ s$
  - $s ::= c0(qt, \dots, qt) \mid \dots \mid cn(qt, \dots, qt)$ 
    - Allow a type qualifier to appear on each type constructor
- For MinML
  - $qt ::= \text{int}^Q \mid \text{bool}^Q \mid qt \rightarrow^Q qt$

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## Abstract Syntax of MinML with Qualifiers

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

- $\text{annot}(Q, e)$  = "expression  $e$  has qualifier  $Q$ "
- $\text{check}(Q, e)$  = "fail if  $e$  does not have qualifier  $Q$ "
  - Checks only the top-level qualifier
- Examples:
  - $\text{fun } \text{fread}(x:qt):\text{int}^{\text{tainted}} = \dots 42^{\text{tainted}}$
  - $\text{fun } \text{printf}(x:qt):qt' = \text{check}(\text{untainted}, x), \dots$

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## Typing Rules: Qualifier Introduction

- Newly-constructed values have "bare" types

$$\frac{}{G \vdash n : \text{int}}$$

$$\frac{}{G \vdash \text{true} : \text{bool}} \quad \frac{}{G \vdash \text{false} : \text{bool}}$$

- Annotation adds an outermost qualifier

$$\frac{G \vdash e1 : s}{G \vdash \text{annot}(Q, e) : Q\ s}$$

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## Typing Rules: Qualifier Elimination

- By default, discard qualifier at destructors

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

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

$$\frac{G \vdash e1 : Qs}{G \vdash \text{check}(Q, e) : Qs}$$

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## 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?

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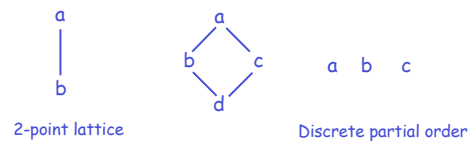
## Partial Orders

- 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`

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## Example Partial Orders



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

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### 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:

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

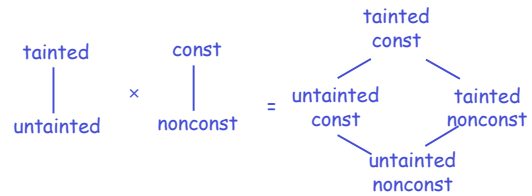
where

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

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### Example



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

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### Extending the Qualifier Order to Types

$$\frac{Q \leq Q'}{\text{bool}^Q \leq \text{bool}^{Q'}} \quad \frac{Q \leq Q'}{\text{int}^Q \leq \text{int}^{Q'}}$$

- Add one new rule *subsumption* to type system

$$\frac{G \vdash e : qt \quad qt \leq qt'}{G \vdash e : qt'}$$

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

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### Use of Subsumption

$$\frac{\frac{\frac{}{|- 42 : \text{int}}{|- \text{annot}(\text{untainted}, 42) : \text{untainted int}}{|- \text{annot}(\text{untainted}, 42) : \text{tainted int}}}{|- \text{check}(\text{tainted}, \text{annot}(\text{untainted}, 42)) : \text{tainted int}} \quad \text{untainted} \leq \text{tainted}}{|- \text{check}(\text{tainted}, \text{annot}(\text{untainted}, 42)) : \text{tainted int}}$$

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## Subtyping on Function Types

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- What about function types?

$$\frac{?}{qt1 \rightarrow^Q qt2 \leq qt1' \rightarrow^{Q'} qt2'}$$

- 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"?

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## Replacing "f x" by "g x"

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

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

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

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## Subtyping on Function Types

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$$\frac{qt1' \leq qt1 \quad qt2 \leq qt2' \quad Q \leq Q'}{qt1 \rightarrow^Q qt2 \leq qt1' \rightarrow^{Q'} qt2'}$$

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

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## Dynamic Semantics with Qualifiers

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

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

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## Dynamic Semantics with Qualifiers (cont'd)

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- 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`)

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## Soundness

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

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## Updateable References

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- Our MinML 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

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## Language Extension

- We'll add ML-style references
  - $e ::= \dots \mid \text{ref}^Q e \mid !e \mid e := e$ 
    - $\text{ref}^Q e$  -- 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)

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## Static Semantics

- Extend type language with references:
  - $qt ::= \dots \mid \text{ref}^Q qt$ 
    - Note: In ML the ref appears on the right

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

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

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## Subtyping References

- The *wrong* rule for subtyping references is

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

- Counterexample
 

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

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## 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



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### Solution #1: Java's Approach

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- 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

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### Solution #2: Purely Static Approach

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- 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:

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

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### Challenge Problem: Soundness

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- 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

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### Type Qualifier Inference

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- 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*

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### Type Qualifier Inference Statement

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- 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

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### Type Checking vs. Type Inference

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- 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

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### Why Do We Want Qualifier Inference?

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- 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

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### First Problem: Subsumption Rule

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$$\frac{G \vdash e : qt \quad qt \leq qt'}{G \vdash e : qt'}$$

- 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)?

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### Getting Rid of Subsumption

- Lemma: Multiple sequential uses of subsumption can be collapsed into a single use
  - Proof: Transitivity of  $\leq$
- So now we need only apply subsumption once after each expression

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### Getting Rid of Subsumption (cont'd)

- We can get rid of the separate subsumption rule
  - Incorporate it directly into the other rules

$$\frac{\frac{G \vdash e1 : qt' \rightarrow^Q qt'' \quad qt1 \leq qt' \quad Q' \leq Q \quad qt'' \leq qt2}{G \vdash e1 : qt1 \rightarrow^Q qt2} \quad \frac{G \vdash e2 : qt \quad qt \leq qt1}{G \vdash e2 : qt1}}{G \vdash e1 e2 : qt2}$$

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### Getting Rid of Subsumption (cont'd)

- 1. Fold  $e2$  subsumption into rule

$$\frac{\frac{G \vdash e1 : qt' \rightarrow^Q qt'' \quad qt1 \leq qt' \quad Q' \leq Q \quad qt'' \leq qt2}{G \vdash e1 : qt1 \rightarrow^Q qt2} \quad G \vdash e2 : qt \quad qt \leq qt1}{G \vdash e1 e2 : qt2}$$

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### Getting Rid of Subsumption (cont'd)

- 2. Fold  $e1$  subsumption into rule

$$\frac{qt1 \leq qt' \quad Q' \leq Q \quad qt'' \leq qt2 \quad \frac{G \vdash e1 : qt' \rightarrow^Q qt'' \quad G \vdash e2 : qt \quad qt \leq qt1}{G \vdash e1 e2 : qt2}}{G \vdash e1 e2 : qt2}$$

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### Getting Rid of Subsumption (cont'd)

- 3. We don't use  $Q$ , so remove that constraint

$$\frac{qt1 \leq qt' \quad qt'' \leq qt2 \quad G \vdash\!\!-\ e1 : qt' \rightarrow^Q qt'' \quad G \vdash\!\!-\ e2 : qt \quad qt \leq qt1}{G \vdash\!\!-\ e1 e2 : qt2}$$

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### Getting Rid of Subsumption (cont'd)

- 4. Apply transitivity of  $\leq$ 
  - Remove intermediate  $qt1$

$$\frac{qt'' \leq qt2 \quad G \vdash\!\!-\ e1 : qt' \rightarrow^Q qt'' \quad G \vdash\!\!-\ e2 : qt \quad qt \leq qt'}{G \vdash\!\!-\ e1 e2 : qt2}$$

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### Getting Rid of Subsumption (cont'd)

- 5. We're going to apply subsumption afterward, so no need to weaken  $qt''$

$$\frac{G \vdash\!\!-\ e1 : qt' \rightarrow^Q qt'' \quad G \vdash\!\!-\ e2 : qt \quad qt \leq qt'}{G \vdash\!\!-\ e1 e2 : qt''}$$

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### Getting Rid of Subsumption (cont'd)

- We apply the same reasoning to the other rules
  - We're left with a purely syntax-directed system
- Good! Now we're half-way to an algorithm

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## Second Problem: Assumptions

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

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

- 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

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## Unknowns in Qualifier Inference

- We've got *regular* type annotations for functions
  - (We could even get away without these...)

$$\frac{G, f: ? \rightarrow^Q ?, x:? \dashv\vdash e : qt2' \quad qt2' \leq qt2}{G \dashv\vdash \text{fun } f^Q(x:t1):t2 = e : qt1 \rightarrow^Q qt2}$$

- How do we pick the qualifiers for  $f$ ?
  - We generate fresh, unknown *qualifier variables* and then solve for them

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## Adding Fresh Qualifiers

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

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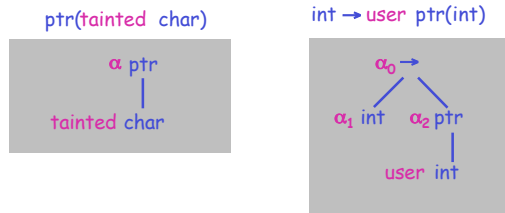
## Rule for Functions

$$\frac{qt1 = \text{fresh}(t1) \quad qt2 = \text{fresh}(t2)}{G, f: qt1 \rightarrow^Q qt2, x:qt1 \dashv\vdash e : qt2' \quad qt2' \leq qt2} \\ G \dashv\vdash \text{fun } f^Q(x:t1):t2 = e : qt1 \rightarrow^Q qt2$$

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## A Picture of Fresh Qualifiers



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## 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

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## 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 security vulnerability

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## Solving Constraints: Step 1

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

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### Solving Constraints: Step 1

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

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### Solving Constraints: Step 2

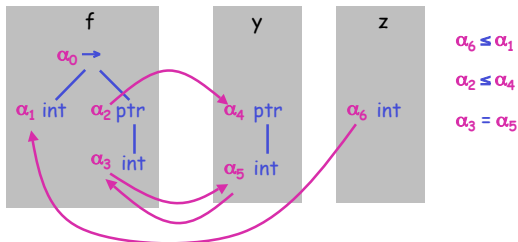
- Our type system is called a *structural subtyping system*
  - If  $\text{qt} \leq \text{qt}'$ , then  $\text{qt}$  and  $\text{qt}'$  have the same shape
- When we're done with step 1, we're left with constraints of the form  $Q \leq Q'$ 
  - Where either of  $Q, Q'$  may be an unknown
  - This is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

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### Constraint Generation

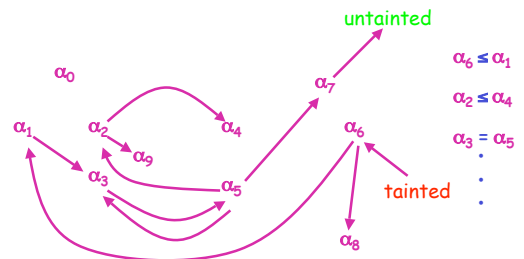
`ptr(int) f(x : int) = { ... }      y := f(z)`



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### Constraints as Graphs



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### Some Bad News

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



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### But That's OK

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- 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

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### Lubs and Glbs

---

- lub = Least upper bound
  - $p \text{ lub } q = r$  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

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### Lattices

---

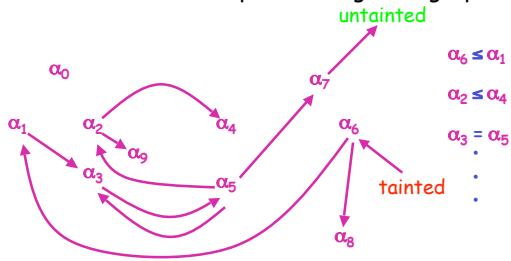
- A *lattice* is a partial order such that lubs and glbs always exist
- If  $\mathcal{Q}$  is a lattice, it turns out we can use a really simple algorithm to check satisfiability of constraints over  $\mathcal{Q}$

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### Satisfiability via Graph Reachability

Is there an inconsistent path through the graph?

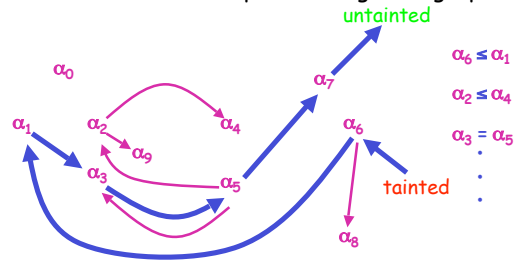


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### Satisfiability via Graph Reachability

Is there an inconsistent path through the graph?

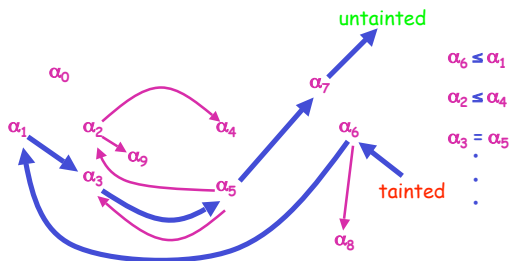


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### Satisfiability via Graph Reachability

$\text{tainted} \leq \alpha_6 \leq \alpha_1 \leq \alpha_3 \leq \alpha_5 \leq \alpha_7 \leq \text{untainted}$



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### 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

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## 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...

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## Limitations of Subtype Polymorphism

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

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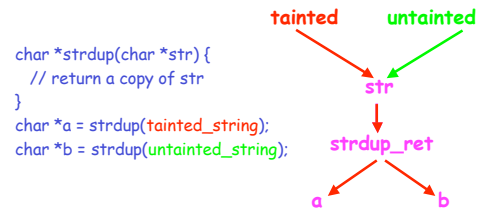
## Types for id

- `fun id (x:int):int = x` (ignoring `int`, qual on `id`)
  - `tainted`  $\rightarrow$  `tainted`
    - Fine but `untainted` data passed in becomes `tainted`
  - `untainted`  $\rightarrow$  `untainted`
    - Fine but can't pass in `tainted` data
  - `untainted`  $\rightarrow$  `tainted`
    - Not too useful
  - `tainted`  $\rightarrow$  `untainted`
    - Impossible

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## Function Calls and Context-Sensitivity



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

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### What's Happening Here?

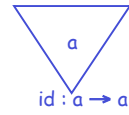
- The qualifier on  $x$  appears both covariantly and contravariantly in the type
  - We're stuck
- We need *parametric polymorphism*
  - We want to give `fun id (x:int):int = x` the type  $\forall a.int^a \rightarrow int^a$

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### The Observation of Parametric Polymorphism

- Type inference on `id` yields a proof like this:



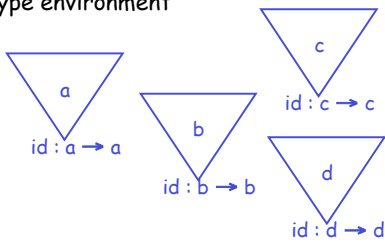
- If we just infer a type for `id`, no constraints will be placed on  $a$

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### The Observation of Parametric Polymorphism

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

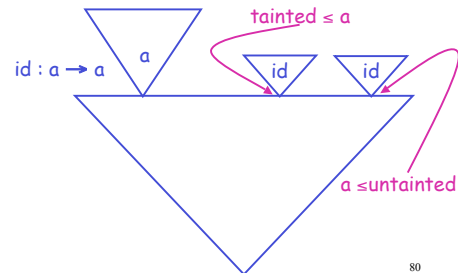


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### The Observation of Parametric Polymorphism

- The constraints on  $a$  only come from "outside"

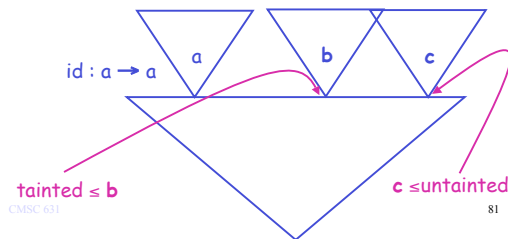


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## The Observation of Parametric Polymorphism

- But the two uses of `id` are different
  - We can inline `id`
  - And compute a type with a different `a` each time



## Implementing Polymorphism Efficiently

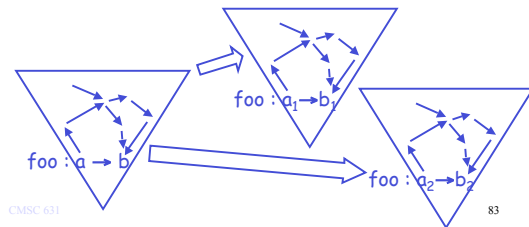
- ML-style polymorphic type inference is EXPTIME-hard
  - In practice, it's fine
  - Bad case can't happen here, because we're polymorphic *only* in the qualifiers
    - That's because we'll apply this to  $C$
- We need polymorphically constrained types
  - $x : \forall a. qt \text{ where } C$
  - For any qualifiers `a` where constraints  $C$  hold, `x` has type `qt`

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## Polymorphically Constrained Types

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



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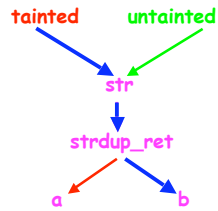
## A Better Solution: CFL Reachability

- 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  $O(n^6)$
- Idea due to Horwitz, Reps, and Sagiv, and Rehof, Fahndrich, and Das

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### The Problem Restated: Unrealizable Paths

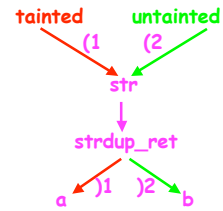


- No execution can exhibit that particular call/return sequence

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### Only Propagate Along Realizable Paths



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

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### Instantiation Constraints

- These edges represent a new kind of constraint
  - $a \leq^i b$
  - At use  $i$  of a polymorphic type
  - Qualifier variable  $a$
  - Is instantiated to qualifier  $b$
  - Either positively or negatively (or both)
- Formally, these are *semiunification* constraints
  - But we won't discuss that

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### Type Rules

- We'll use Hindley-Milner style polymorphism
  - Quantifiers only appear at the outmost level
  - Quantified types only appear in the environment

$$\frac{qt1 = \text{fresh}(t1) \quad qt2 = \text{fresh}(t2) \quad G, f: qt1 \rightarrow^Q qt2, x:qt1 \vdash e : qt2' \quad qt2' \leq qt2}{G \vdash \text{fun } f^Q(x:t1):t2 = e : qt1 \rightarrow^Q qt2}$$

- \* This is not quite the right rule, yet...

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## Type Rules

$$\frac{qt = G(f) \quad qt' = \text{fresh}(qt) \quad qt \leq+i qt'}{G \dashv\vdash f_i : qt'}$$

- Implicit: Only apply to function names ( $f$ )
- Each has a label  $i$
- $\text{fresh}(qt)$  generates type like  $qt$  but with fresh quals
  - \*This is not quite the right rule yet...

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## Resolving Instantiation Constraints

- Just like subtyping, reduce to only qualifiers
  - $S + \{ \text{int}^Q \leq \text{pi int}^{Q'} \} \Rightarrow S + \{ Q \leq \text{pi } Q' \}$ 
    - $p$  stands for either  $+$  or  $-$
  - ...
  - $S + \{ qt1 \rightarrow^Q qt2 \leq \text{pi } qt1' \rightarrow^{Q'} qt2' \} \Rightarrow$   
 $S + \{ qt1 \leq (-p)i qt1' \} + \{ qt2 \leq \text{pi } qt2' \} + \{ Q \leq \text{pi } Q' \}$ 
    - Here  $-(+)$  is  $-$  and  $-(-)$  is  $+$

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## Instantiation Constraints as Graphs

- Three kinds of edges

-  $Q \leq Q'$  becomes  $Q \longrightarrow Q'$

-  $Q \leq+i Q'$  becomes  $Q \xrightarrow{i} Q'$

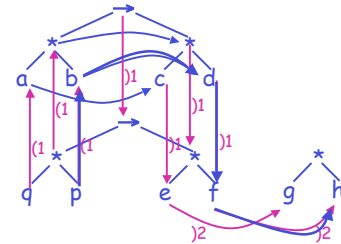
-  $Q \leq-i Q'$  becomes  $Q \xleftarrow{i} Q'$

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## An Example (Stolen from RF01)

```
fun idpair (x:int*int):int*int = x in
fun f y = idpair1 (3q, 4p) in
let z = snd (f2 0)
```



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## Two Observations

- We are doing constraint copying
  - Notice the edge from **b** to **d** got "copied" to **p** to **f**
    - 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

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## 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

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## CFL Reachability Grammar

```

S ::= P N
P ::= M P
   | ) i P
N ::= M N
   | ( i N
M ::= ( i M ) i
   | M M
   | d

```

for any i  
empty

for any i  
empty

for any i  
empty

regular subtyping edge  
empty

- Paths may have **unmatched** but not **mismatched** parens

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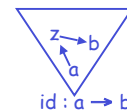
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## Global Variables

- Consider the following identity function
 

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

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

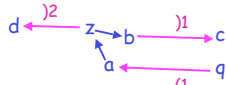


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## Global Variables

- 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 pop out at  $d$

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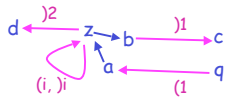
## Thou Shalt Not Quantify a Global Type (Qualifier) Variable

- 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!

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## 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

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## Typing Rules, Fixed

- Track unquantifiable vars at generalization

$$\begin{array}{c}
 qt1 = \text{fresh}(t1) \quad qt2 = \text{fresh}(t2) \\
 G, f: (qt1 \rightarrow^Q qt2, v), x:qt1 \dashv\vdash e: qt2' \quad qt2' \leq qt2 \\
 v = \text{free vars of } G \\
 \hline
 G \dashv\vdash \text{fun } f^Q(x:t1):t2 = e: (qt1 \rightarrow^Q qt2, v)
 \end{array}$$

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## Typing Rules, Fixed

---

- Add self-loops at instantiation

$$\frac{\begin{array}{l} (qt, v) = G(f) \quad qt' = \text{fresh}(qt) \quad qt \leq+i qt' \\ v \leq+i v \quad v \leq-i v \end{array}}{G \vdash f_i : qt'}$$

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## 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

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## Security via 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
    - (Haven't applied it to security)
- Suppose we want to apply this to a language like C
  - It doesn't quite look like MinML!

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## 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!

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## 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*

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## Mapping to MinML

- Variables will have ref types:
  - `x : refQ <contents type>`
  - Parameters as well, but r-types in fn sigs
- On rhs of assignment, add *deref* of variables

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

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## 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)

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### Multiple Files: Solution #1

- Don't analyze programs with multiple files!
- Can use CIL merger from Nacula 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

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### 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

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### 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


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### 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)



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## 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

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## Structures: Scalability Issues

---

- Second problem: Multiple Instances
  - Naively, 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!

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## 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

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## Subtyping Under Pointer Types

---

- Recall we argued that an updateable reference behaves like an object with get and set operations
- Results in this rule:
$$\frac{Q \leq Q' \quad qt \leq qt' \quad qt' \leq qt}{\text{ref}^Q qt \leq \text{ref}^{Q'} qt'}$$
- What if we can't write through reference?

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### 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

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

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### 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

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### Presenting Inference Results

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### Type Casts

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### 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

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### Results: Format String Vulnerabilities

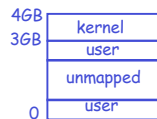
Name	Warn	Bugs
identd-1.0.0	0	0
mingetty-0.9.4	0	0
bftpd-1.0.11	1	1
muh-2.05d	2	~2
cfengine-1.5.4	5	3
imspd-4.7c	0	0
ipopd-4.7c	0	0
mars_nwe-0.99	0	0
apache-1.3.12	0	0
openssh-2.3.0p1	0	0

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### 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

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### 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

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## 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!

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## 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`

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## 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

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## 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

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## 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

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## 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* (green box) points to `int x;`

`copy_from_user(&x, p, sizeof(x));` has two `OK` (green boxes) annotations: one pointing to `copy_from_user` and one pointing to `&x`.

`memcpy(p, &x, sizeof(x));` has an `Error` (red box) annotation pointing to `memcpy`.

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## 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 dereference it without a check

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## 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 `refuser(Q s)`, it must be that `Q ≤ user`
  - This is a *well-formedness* condition on types

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## Well-Formedness Constraints

- As a type rule

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

- 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  $Q \leq Q'$

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## Well-Formedness Constraints

- Use conditional constraints

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

- "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

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## Well-Formedness Constraints

- Similar constraints for `struct` types

$$\frac{\text{For all } i, |--wf(Q_i s_i) \quad Q \leq \text{user} \implies Q_i \leq \text{user}}{|--wf \text{struct}^Q(Q_1 s_1, \dots, Q_n s_n)}$$

- Again, can specify this per-qualifier

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## 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_ioctl_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;
            }
        }
    }
```

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## 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_ioctl_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;
        }
    }
}
```

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## 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_ioctl_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;
        }
    }
}
```

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## 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_ioctl_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;
        }
    }
}
```

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## 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 been done automatically (All begin with sys\_)
- Ran both single file (unsound) and whole-kernel
  - Disabled subtyping for single file analysis

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## More Detailed Results

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- 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

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## Observations

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- 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!

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## Observations

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- 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

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## Conclusion

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

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