Enforcing C-level security policies
using machine-level tags

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HW for better SW security

• Problem space: security for legacy software...
  • Especially in unsafe languages like C/C++

• ...using hardware support for reference monitors...
  • Processor extensions to handle metadata

• ...with a new focus on higher-level properties
  • Expressed in source-language terms
  • Extending beyond simple safety
  • Trusting or verifying the compiler
Outline

- Reference monitors and the PIPE
- ISA-level Tag-based policies
- C-level policies
- Semantics and implementation
- Conclusions
Reference Monitors and the PIPE
Reference Monitors

- **Explicitly** check every potentially dangerous operation
  - e.g. “is this memory reference in bounds?” “is this top-secret value being written to an insecure channel?” “is this a valid address to jump to?”

- Useful when we don’t trust program and/or programming language

- Works for any **safety** property (“this bad thing does not happen”)
  - Doesn’t work for **liveness** properties (“this good thing does happen”)

- Gives “fail-stop” behavior
  - No direct support for recovering and continuing
Examples of safety policies

• “No secret data leak to a public output channel.”

• “Every store operation occurs to a valid memory location.”

• “The processor only jumps to places the programmer intended.”

• “Code modules communicate only via their specified interfaces.”
Example: confidentiality

- Data comes from secret or public sources
  - \( x = \text{read}\_\text{secret}(); \ y = \text{read}\_\text{public}(); \)

- Any result of operating on secret data should also be treated as secret
  - \( z = x + y; \ // \ z \text{ is secret } \Leftrightarrow \ x \text{ or } y \text{ is secret} \)

- Attempting to output secret data to a public channel should halt the program
  - \( \text{write}\_\text{public}(z); \ // \text{halt if } z \text{ is secret} \)
Example: compartments

- Code is divided into compartments with explicit interfaces
- Inter-compartment access is mediated according to access control matrix
- Attempting an invalid access should halt the program

```
int foo@A[5]; // compartment A
int bar@A(int i) { // compartment A
    return foo[i];
}
int main@B() { // compartment B
    return bar(3);
}
```

<table>
<thead>
<tr>
<th></th>
<th>Main</th>
<th>Foo</th>
<th>Bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>—</td>
<td>Read, Write</td>
<td>Call</td>
</tr>
<tr>
<td>B</td>
<td>Call</td>
<td>—</td>
<td>Call</td>
</tr>
</tbody>
</table>
Example: memory safety

• Each pointer is associated with a precise region of memory

• Attempting to use a pointer to access outside its region or to access a deallocated region should halt the program

• In C/C++ this protects against one class of "Undefined Behaviors" (UB)

• Safe languages normally enforce this in software
Monitoring in Hardware

- Implementing monitors in software can be very slow
- So, let's use silicon to improve security, not just performance
- Perform monitoring in parallel with normal execution, to avoid adding delay
- Checks occur at machine level, so cannot be evaded by buggy or malicious software
- Challenge: how to make hardware flexible enough to handle changing threats
Simplified PIPE Architecture

Typical RISC CPU

+ large tag on every word

+ tag management unit (rule cache)

(costs extra ~100% in area and ~50% in power)
Tag Management Unit

acts like a cache

key

(Opcode, pc-tag, instruction-tag, register-operand1-tag, register-operand2-tag, memory-operand-tag)

result

(new-pc-tag, result-tag)

if key is not present, control traps to tag miss handler
Tag Miss Handler

- Ordinary machine code that lives at special location in OS (or runs on a special co-processor)
- Takes missing key as input
- Executes tagging decision algorithm
  - Hardware is completely independent of this algorithm
- EITHER generates result tags & stores in TMU cache
  - Instruction that faulted is then restarted
- OR discovers security violation and fail-stops the process (or whole processor)
PIPE performance

• Runtime cost depends on cache hit rate
• Varies widely for different choices of policies and program patterns
• Simulations using SPEC2006 benchmarks enforcing a fairly rich composite policy show <10% added runtime for most programs
• Keeping number of “live” tags low is essential
  • Also important for fault handler to run fast
Tag-based Policies
Anatomy of a policy

• **Set of tags** for labeling registers, memory, PC
  • Can be discrete symbols, numbers, or **addresses** pointing to arbitrarily complicated data structures

• **Rules** for checking and propagating tags as the machine executes each instruction
  • Rules can be arbitrarily complex and may maintain a persistent internal database
  • But they must be monotonic

• **Initial configuration**
  • Tags on memory contents; state of tag rule database

Policies are written in a domain-specific language
IFC Policy

- **Goal**: ensure that secret data does not flow to public output
  - or, dually, ensure that public input data does not taint private data
- **Tag = Value from security lattice, e.g.**
  - attached to each data value
  - also attached to PC to record implicit flows
- **Rules**:
  - Computations produce result value tagged with join of argument value tags and PC tag
  - Conditional tests raise PC to join of argument values
  - Public values cannot be generated when PC is tagged secret
**IFC example**

**user code**

...  
`add r1,r2,r3`  
`add r4,r3,r5`  
...

**tag miss handler**

**symbolic rules**

`add(L1,L2) → max(L1,L2)`  
...

**software**

**hardware**

**restart**

**trap**

**install**

**registers**

`r1:3@secret`
`r2:2@secret`
`r3:9@public`
`r4:3@public`
`r5:7@public`

**alu**

**cpu**

**tmu**

**rule cache**

`add(public,public) → public`
`add(secret,secret) → secret`
`add(public,secret) → secret`

**secret > public**
Example: Static Compartments

- **Goal:** Divide process memory into set of disjoint compartments which are protected from each other
  - Code in one compartment can jump or write to other compartments only at a pre-defined set of addresses (an interface)

- **Tags = compartment ID or set of compartment IDs**
  - PC is tagged with current compartment
  - Each memory location is tagged with set of compartments that can validly access it

- **Rules:**
  - On each write and after each branch, compare PC tag with tag of memory location being written or executed
Example: Heap Memory Safety

• Goal: prevent heap buffer overflows

• Tags = ValueTag | Cell(region#,ValueTag) where ValueTag = NonPtr | Ptr(region#)
  • Each call to malloc generates a fresh integer region# tag c -- a "color"
  • Pointer to new region is tagged Ptr(c)
  • All other values are tagged NonPtr
  • Values in newly-allocated memory cells are tagged with Cell(c,v) where v is tag of value in cell

• Rules:
  • Load and store instructions check that address pointer is tagged Ptr(c) and the referenced memory cell is tagged Cell(c, _)
  • Pointer arithmetic instructions preserve Ptr(c) tags
Heap Memory Safety Example
Heap Memory Safety Example

```c
int *x = malloc(3);
y = 10;
x[0] = y;
```
Heap Memory Safety Example

Variables

Memory

int *x = malloc(3)
y = 10
x[0] = y

int *z = malloc(5)
x[2] = (int) z
Heap Memory Safety Example

```
int *x = malloc(3)
y = 42
x[0] = y

int *z = malloc(5)
x[2] = (int) z

int *v = x[2] + 2
v[0] = y
```
int *x = malloc(3)
y = 42
x[0] = y

int *z = malloc(5)
x[2] = (int) z

int *v = (int *) x[2] + 2
v[0] = y

int *w = x + 3
w[0] = y
```
int *x = malloc(3)
y = 42
x[0] = y

int *z = malloc(5)
x[2] = (int) z

int *v = (int *) x[2] + 2
v[0] = y

int *w = x + 3
w[0] = y

free(x)
x[0] = 100
```
Composing policies

• In practice we want to compose policies

• Many policies are essentially orthogonal
  • e.g. A = Memory safety and B = IFC
  • Make tags be pointers to pairs (Atag,Btag)
  • Operations are allowed only if both policies say OK

• But others are not…
  • e.g. A = Memory safety and B = Compartments
  • because memory tags for these must be coherent

• General theory is a subject of ongoing research
C-Level Policies
Problem and Opportunity

• It is hard to specify and enforce some safety policies at hardware ISA level
  • No typing information
  • No structured control flow
  • Function boundaries and calling conventions may be obscured

• How about working directly at the level of C code instead?
  • Tie tag-based monitoring to C code execution points
  • Avoid reverse engineering of compiled code
  • Support specifying policies at higher level of abstraction
Approach

- Use tagging rules during C execution
  - Add monitoring/control points to C semantics
  - Customize by per-system or per-program rules
  - Compile to ISA-level tags for runtime enforcement

- Express high-level policies with rules
  - Fine-grained information flow control
  - Compartment enforcement and access control

- Combine with fixed base policy
  - Trap C undefined behaviors on pointers
Example: IFC in more detail

- **Goal:** prevent leakage of high-security information
- **Tags = Security labels from a lattice**
  - Initial memory values and pointers are labelled
  - PC carries “current” label
- **Rules:**
  - Instructions that move values propagate labels
  - Binary operations compute lattice join of labels
  - Conditional jumps raise PC label level based on inspected value
  - “No sensitive upgrade” — stores are prevented if PC is higher than old value, thus avoiding “implicit flows”

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![Secret | Public example](image)
IFC: example program

```c
int f (int x, int y) { // assume x value secret, y value public
    if (x > 0)
        y = 42; // bad: sensitive upgrade
    y = y + 1; // ok: not under control of secret
    return y;
}
```

Implicit flow if public return in y depends on secret x

Calling `f (1, 100)` should trigger tag violation

Calling `f (0, 100)` should not trigger tag violation

Assumes that attacker cannot (efficiently) observe when tag violations occur (gives "error-insensitive non-interference")
ISA-level tagging: “label creep”

function f: // args in r0, r1
0  : Mov  r0 r2  // fetch arg0
1  : Brnz r2 3  // if arg0 > 0 goto 4
2  : Const 1 r6  // goto 6
3  : Brnz r6 3  //
4  : Const 42 r5  // get 42
5  : Mov  r5 r1  // store into arg1
6  : Mov  r1 r7  // fetch arg1
7  : Const 1 r8  // add 1
8  : Add  r8 r7  // to arg1 value
9  : Mov  r7 r1  // store back in arg1
10 : Mov  r1 r9  // fetch arg1
11 : Ret  r9  // and return it
12 : Halt

brnz pc_tag arg_tag := OK (pc_tag ∨ arg_tag)
mov pc_tag src_tag tgt_tag :=
    if pc_tag ≤ tgt_tag then OK (pc_tag ∨ src_tag) else FAIL

Calling f (1,100) triggers **tag violation** ✓
Calling f (0,100) also triggers **tag violation** ✗
C-level tagging

- Express tagging policy at level of C expression operators and control structures, rather than of machine instructions
- Attach tags to C “program counter,” values, memory locations (globals, malloc’ed heap records, …), functions, …
- Tag rules are invoked at fixed set of control points in C execution semantics
  - instead of at each instruction
  - similar to aspect-oriented programming “advice” points
Assumptions

• **Access to C source code**
  • But little or no ability to edit it

• **All object code is produced by our custom compiler**
  • Compiler is in TCB; we must trust or (better) verify it

• **May want to “bake in” some policies**
  • To guard against some C undefined behaviors
Set of control points is defined once and for all for the C language.

```c
int f (int x, int y) {
    if (x > 0)
        y = 42;
    y = y + 1;
    return y;
}
```
int f (int x, int y) {
    if (x > 0)
        y = 42;
    y = y + 1;
    return y;
}

ifSplitT v_tag pc_tag := OK (v_tag v pc_tag)
ifJoinT v_tag old_pc_tag pc_tag := OK old_pc_tag
assignT pc_tag v_tag old_v_tag :=
    if pc_tag ≤ old_v_tag then
        OK (pc_tag v v_tag)
    else FAIL

rules are parameterized on tags of all relevant values and PC

PC tag is reset at join point, so second assignment is OK
Example: Compartments sharing data

- **Goal**: use interfaces to control how one compartment shares data with another

- **Tags** as in Memory safety policy, but with
  - Value Tags = NonPtr | Pointer(a,c)
    - where a is an access level = ReadOnly | ReadWrite
  - and PC Tag = Function ID

- **Auxiliary configuration data maps defines**
  - Compartments = sets of Function ID's and says which compartments grant which other compartments write access
Example program

```c
void f@A (int *p) { *p = 1; }
void g@A () { int *q = malloc(1); f(q); }
void main@B () { int *r = malloc(1); g(); f(r); }
```

Assume access control configuration defines
A = \{f, g\}, B =\{h, main\}
and A has only read access to data allocated by B.

Store in first call to f (from g) should succeed;
store in second call (from main) should fail.

Rules:

- Each array malloc generates a fresh region "color" c and resulting pointer is tagged Pointer(ReadWrite,c)
- Memory writes require Pointer(ReadWrite,_); reads require only Pointer(_,_)  
- On function calls, each pointer argument is potentially "downgraded" from ReadWrite to ReadOnly based on PC tags of caller, callee
Using fewer colors

- Should we really allocate a separate color for each malloc'ed buffer?
  - + Gives fine-grained control over sharing
  - + Prevents one class of C undefined behaviors
  - - Puts lots of pressure on the tag cache

- Idea: to control sharing, we only need to distinguish regions that we actually might share
  - according to programmer or (since we trust the compiler) an escape analysis
Using fewer colors (2)

- Distinguish definitely "private" buffers from potentially "sharable" buffers
- Each "Sharable" buffer gets a fresh color
- "Private" buffers are all given a single per-compartment color
- Trade-off: we no longer get as much intra-component protection against memory UBs
Semantics and Implementation
Architecture

• To use tagged C for a specific policy:
  • define vocabulary of tags and tag operators (just as for machine-level tagging)
  • instantiate rules for each control point

• To use it for a specific C program:
  • specify tag information for (at least) link-level C entities including functions and globals
  • ideally we will not need to change the C code

• Policies can be specified per system, per module or even per function
More detailed example: statements

One clause in C statement semantics

```c
IfS e s1 s2 =>
  v@v_tag <- eval e;
  pc_tag_0 <- get_pc_tag;
  pc_tag_1 <- ifSplitT v_tag pc_tag_0;
  set_pc_tag pc_tag_1;
  if v then exec s1 else exec s2;
  pc_tag_2 <- ifJoinT v_tag pc_tag_0 pc_tag_1;
  set_pc_tag pc_tag_2
```

An instantiation for IFC tags:

```
Tag = PUBLIC | SECRET

ifSplitT v_tag pc_tag := OK (v_tag \ pc_tag)
ifJoinT v_tag old_pc_tag pc_tag := OK old_pc_tag
```

designed once and for all

written once for each policy (in policy DSL)
More detailed example: expressions

One clause in C expression semantics

```
| PlusE e1 e2 =>
v1@t1 <- eval e1;
v2@t2 <- eval e2;
t <- plusT t1 t2;
ret (v1+v2)t
```

An instantiation for IFC tags:

```
Tag = PUBLIC | SECRET

plusT v1_tag v2_tag := OK(v1_tag \ v2_tag)
```

An instantiation for memory safety tags:

```
Tag = NotPtr | Ptr region

plusT v1_tag v2_tag :=
match v1_tag,v2_tag with
| NotPtr, NotPtr => OK NotPtr
| Ptr a, NotPtr => OK (Ptr a)
| NotPtr, Ptr a => OK (Ptr a)
| _, _, _ => FAIL
end.
```
Compilation

• Go from tagged C to tagged machine code

• Basic idea: specially tag the instructions in the generated code to indicate their C-level role
  • Machine-level rules for these special tags are built directly from the C-level rules
  • Must modify compiler (to generate appropriately tagged instructions)
  • Compilation scheme is independent of policy (although policy-specific schemes might give better code)
Compilation Example

One clause in C expression semantics

```c
| PlusE e1 e2 =>
  v1@t1 <- eval e1;
  v2@t2 <- eval e2;
  t <- plusT t1 t2;
  ret (v1+v2)@t
```

Corresponding clause in C expression compiler

```c
compileExp (e: Exp) : (reg * list Inst) =
...
| PlusE e1 e2 =>
  let (r1,code1) := compileExp e1 in
  let (r2,code2) := compileExp e2 in
  let r := fresh_reg() in
  (r, code1 ++
   code2 ++
   [MovI @ Icopy r1 r] ++
   [AddI @ Iplus r2 r])
```

Machine-level rules (defined once and for all)

- MovI,tpc,Icopy,t1,_,_,_,_ -> tpc,t1,_
- AddI,tpc,Iplus,t1,t2,_,_,_-> tpc,plusT t1 t2,
\[
\text{IfS } e \text{ s1 s2} \Rightarrow
\begin{array}{l}
\text{let (r, is) := compileExp } e \text{ in} \\
\text{let rt := fresh_reg() in} \\
\text{let rt' := fresh_reg() in} \\
\text{let is1 := compileStm } s1 \text{ in} \\
\text{let is2 := compileStm } s2 \text{ in} \\
\text{is ++} \\
\text{getpctag rt ++} \\
\text{combine } r \text{ rt IifSplitT rt' ++} \\
\text{setpctag rt' ++} \\
\text{[BrnzI } r \text{ (length is2+1) @ X] ++} \\
\text{is2 ++} \\
\text{[BrI (length is1) @ X] ++} \\
\text{is1 ++} \\
\text{combine rt rt' IifJoinT rt ++} \\
\text{setpctag rt}
\end{array}
\]

\text{where}

\[
\begin{array}{l}
\text{getpctag } r := [\text{ConstI } @ \text{Igetpctag } 0 \ r] \\
\text{setpctag } r := [\text{ConstI } @ \text{Isetpctag } 0 \ r] \\
\text{combine } r1 r2 I r3 := [\text{MovI } @ \text{Icopy } r1 r3] ++ [\text{MovI } @ I r2 r3]
\end{array}
\]

\text{Machine-level rules (defined once and for all)}

\[
\begin{array}{l}
\text{ConstI,tpc,Igetpctag,_,_,_,_} \rightarrow tpc, tpc, _ \\
\text{ConstI,_,Isetpctag,new_tpc,_,_,_} \rightarrow \text{new_tpc, new_tpc, _} \\
\text{MovI,tpc,Icopy,t1,_,_,_} \rightarrow tpc, t1, _ \\
\text{MovI,tpc,IfsplitT,t1,t2,} \rightarrow tpc, \text{ifSplitT } tpc \ t1 \ t2 \\
\text{MovI,tpc,IfjoinT,t1,t2,} \rightarrow tpc, \text{ifJoinT } tpc \ t1 \ t2
\end{array}
\]

\text{saved tags are attached to dummy values} \\
\text{(spilling if necessary just as for real values)}
Compiler Verification

- Compiler is now part of TCB, so ideally it should be verified

- First experiment (work in progress): verify semantic preservation for a tagged analog to the RTLGen phase of CompCert

- Longer-term goal: integrate with rest of CompCert pipeline, targeting RISC-V

C-like exprs/stmts with tags \[\xrightarrow{\text{tag-preserving}}\] Instruction-level CFG with tags

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Conclusions
Summary

• Expressing tag policies at C level extends the range of properties that we can enforce using the PIPE

• These extensions rely heavily on having higher-level semantic "hooks"

• We have a plausible compilation scheme

• But, the compiler must be trusted or verified
Status

- Have proof-of-concept compiler for toy versions of source language, machine, and policies
  - Source: while, if, functions, global arrays, local variables, malloc
  - Target: infinite register machine with argument marshaling primitives
  - Policies: IFC, compartments, memory safety
  - Verification of semantic preservation is in progress
Ongoing work

• Continuing to extend toy source language with more features of full C
  • types and casts, addressable locals, function ptrs, …
  • non-structured control flow?

• Designing, implementing, and validating compartmentalization policies

• Verification experiments with toy compiler
Some Open Questions

- How much can/should we modify C code?
  - e.g. tags on parameters, local variables?
  - who will be the “security engineer” applying policies?

- How should we handle C undefined behaviors?
  - Any properties enforced by C-level policies hold only if the C code does not trigger undefined behavior (UB)
  - We can detect some memory-based UBs using tag policies
  - Should we "bake in" these policies?

- What about alternatives to C?
  - lower-level, e.g. LLVM-based
  - higher-level, e.g. safe structured languages