C-level Tag-Based Security Monitoring

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(a cast of 1000s)

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Idea in a nutshell

- Many useful safety "μpolicies" can be enforced by reference monitors based on HW metadata tags
  - E.g. info flow control, memory safety, control-flow integrity,…
  - Tag-based policies are specified and enforced at level of HW ISA
- Can we harness tag hardware for efficient enforcement of safety properties defined at level of C code?
  - Add reference monitor points to C semantics
  - Customize by per-system or per-program rules
  - Compile to ISA-level tags for runtime enforcement
- Some possible uses: fine-grained IFC, compartment enforcement, access control, trapping C undefined behaviors

Outline

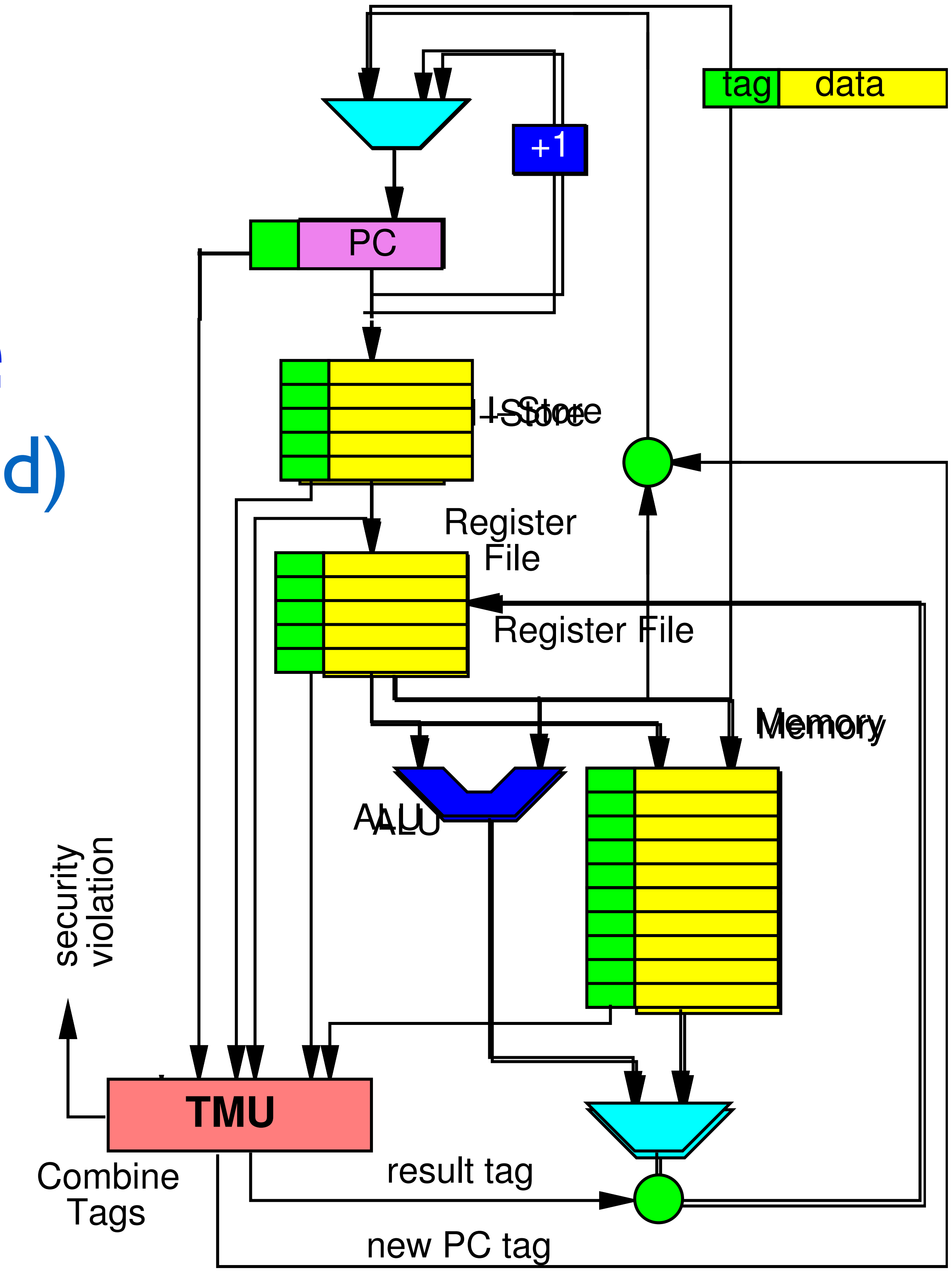
- SAFE/PUMP/PIPE tag hardware architecture
  - Example ISA-level μpolicies
- C-level monitoring
  - Applications
- Compilation scheme
- Open questions

Tag Architecture
(simplified)

Typical RISC CPU

+ large tag on every word

+ tag management unit (rule cache)



Tag Management Unit

acts like a cache

tag is arbitrary bit vector,
usually address
of a data structure

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 in privileged code space or 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 can then complete
- OR discovers security violation and fail-stops the process (or whole processor)

Anatomy of a policy

- Set of tags for labeling registers, memory, PC
  - Can be discrete symbols, numbers, or addresses pointing to arbitrary data structures
- Rules for checking and propagating tags as the machine executes each instruction
  - Rules are just arbitrary code and may maintain persistent internal state
  - But they should be functional (given input tags always produce same output tag)
- Initial configuration
  - Tags on memory contents; tag rule state

Ex: Dynamic Info Flow Control

- Goal: prevent leakage of high-security info
- 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
  - "No sensitive upgrade" — stores are prevented if pointer or PC is higher than old value

Ex: Heap Memory Safety

- Goal: prevent heap buffer overflows
- In-register tags VTag = NotPtr | Ptr Region#
- In-memory tags MTag = (Region#,VTag)
  - Each call to malloc generates a fresh integer region# tag R
  - Newly allocated memory cell values are tagged with (R,…)
  - Pointer to new region is tagged Ptr R
- Rules:
  - Load and store instructions check that address pointer is tagged Ptr R and the referenced memory cell value is tagged (Ptr R,…)
  - Pointer arithmetic instructions preserve Ptr R tags

Ex: Control-flow integrity

- Goal: make sure that every executed jump instruction follows a specified control-flow graph edge
  - e.g. produced by the compiler
- Tag = Data | Code *addr* | Code ⊥
  - Code at location *addr* is given tag Code *addr* iff it is the source or target of a legitimate CFG edge
- Rules:
  - Normally, PC tag is Code ⊥
  - On a jump, check that tag of jumping instruction has the form Code *addr*, and copy it into PC tag
  - If PC tag is Code *saddr* and current instruction is tagged Code *taddr*, require that (*saddr* →*taddr*) is an edge in the CFG

Ex: Dynamic Compartments

- Idea: 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 = sets 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

Composing policies

- Policies are easily composed when they are essentially orthogonal
  - e.g. A = Memory safety and B = CFI
  - Make tags be pointers to pairs (Atag,Btag)
  - Operations are allowed only if both policies say OK
  - When policies interact, things are not so simple…

Tag system performance

- Current designs cost ~100% extra area and ~50% extra power
- Runtime overhead 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 run time for most programs
- Keeping number of "live" tags low is essential

What could be better?

- Policies are tedious to specify at the ISA level
- Some policies are impractical on unstructured code
  - e.g. simple IFC induces label creep
- Inconvenient to express per-program policies
- Although machine-level checking seems very strong, in practice we rely on compiler tool chain to give us good initial tags
- So, what if we include compiler in TCB and try to express policies in a "C-level" way?

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 transfer functions are invoked at fixed set of points in C execution semantics
  - instead of at each instruction
  - similar to aspect-oriented programming “advice” points

What it looks like

- To use tagged C for a specific policy:
  - define vocabulary of tags and tag operators (just as for machine-level tagging)
  - instantiate all the transfer functions.
- To use it for a specific C program:
  - specify tag information for (at least) link-level C entities including functions and globals
  - ideally we do not change the C code
- Policies can be specified per system, per module or even per function

Example

One clause in C statement semantics (monadic style)

```
| IfS e s1 s2 =>
    v@v_tag <- eval e;
    old_pc_tag <- get_pc_tag;
    new_pc_tag <- ifSplitT v_tag old_pc_tag;
    set_pc_tag new_pc_tag;
    if v then exec s1 else exec s2;
    new_pc_tag <- ifJoinT v_tag old_pc_tag new_pc_tag;
    set_pc_tag new_pc_tag
```

this is designed once and for all

An instantiation for IFC tags:

```
Tag = LOW | HIGH

ifSplitT v_tag old_pc_tag := ret(v_tag \/ old_pc_tag)
ifJoinT v_tag old_pc_tag new_pc_tag := ret old_pc_tag
```

this is written once for each policy (in some suitable policy language)

Example

One clause in C expression semantics (monadic style)

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

this is designed once and for all

An instantiation for IFC tags:

```
Tag = LOW | HIGH

plusT v1_tag v2_tag := ret (v1_tag \/ v2_tag)
```

these are written once for each policy

An instantiation for memory safety tags:

```
Tag = NotPtr | Ptr region

plusT v1_tag v2_tag :=
   match v1_tag,v2_tag with
   | NotPtr, NotPtr => retT NotPtr
   | Ptr a,  NotPtr => retT (Ptr a)
   | NotPtr, Ptr a  => retT (Ptr a)
   | _,      _      => failT
   end.
```

What is it good for?

- Can express policies that depend on structured control flow, such as fine-grained IFC within a procedure
- Function-level tags are natural way to enforce access control on resources
- Can express a variety of compartmentalization schemes
- Selective detection of C undefined behaviors, e.g. for pointer safety
  - Assume very permissive compiler and use tag policies to enforce desired level of standards compliance

Compilation

- How to 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 transfer functions for these special tags are built directly from the C-level transfer function
  - Probably 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

```
| 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

```
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 r1 r @ Icopy,
       AddI r2 r @ Iplus])
```

Machine-level rules (defined once and for all)

```
MovI,tpc,Icopy,t1,_,_,_ -> tpc,t1,_
AddI,tpc,Iplus,t1,t2,_,_-> tpc,plusT t1 t2,_
```

```
| IfS e s1 s2 =>
   let (r,is) := compileExp e in
   let rt := fresh_reg() in
   let rt' := fresh_reg() in
   let is1 := compileStm s1 in
   let is2 := compileStm s2 in
   is ++
   getpctag rt ++
   combine r rt IifSplitT rt’ ++
   setpctag rt’ ++
   [BifI r (length is2+1) @ Idontcare] ++
   is2 ++
   [BrI (length is1) @ Idontcare] ++
   is1 ++
   combine rt rt’ IifJoinT rt ++
   setpctag rt
```

```
getpctag r := [ConstI 0 r @ Igetpctag]
setpctag r := [ConstI 0 r @ Isetpctag]
combine r1 r2 I r3 := [MovI r1 r3 @ Icopy] ++
                      [MovI r2 r3 @ I]
```

Machine-level rules (defined once and for all)

```
ConstI,tpc,Igetpctag,_,_,_,_      -> tpc,tpc,_
ConstI,_,Isetpctag,new_tpc,_,_,_  -> new_tpc,new_tpc,_
MovI,tpc,Icopy,t1,_,_,_           -> tpc,t1,_
MovI,tpc_,IifsplitT,t1,t2,_       -> tpc,ifSplitT tpc t1 t2
MovI,tpc,IifjointT,t1,t2,_        -> tpc,ifJoinT tpc t1 t2
```

Attacker Model and TCB

- Initial assumption is that all object code is produced by this compiler, and we rely on correctness of compiler and linker/loader
  - Trust; ideally verify.
- If our C code might have undefined behaviors, we may wish to guard against these using a combination of C-level policies and some "built-in" ISA-level policies, e.g. RWX permissions, correct call bracketing, CFI, …
- Those ISA-level policies will also be needed if we want to link against code of unknown provenance

Some Open Questions

- How much should we modify C code?
  - e.g. tags on parameters, local variables?
  - is it realistic to deal with dusty decks anyhow?
- Could we use software enforcement for C level tags?
- What is a good C component specification scheme?
- Who is the "security engineer" responsible for applying policies?