Secure Program Execution via Dynamic Information Flow Tracking

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Program Vulnerabilities

- Program bugs cause serious security risks
  - Attackers can gain total control of victim processes
  - Very difficult, if not impossible, to eliminate the bugs

- Existing solutions have limitations
  - Safe languages → re-programming, performance hit
  - Fix programs: new libraries, compilers
    → partial protection, re-compilation
  - Run-time monitoring: program shepherding
    → overheads
  - Other hardware solutions → partial protection

Our Goal

- Architectural support to defeat a broad range of security exploits (possibly all)
  - Focus on attacks to gain total control (shell)
  - Should work for legacy code and shared libraries
    → transparent to applications, run-time checks
  - Should have low overhead (performance and memory space)

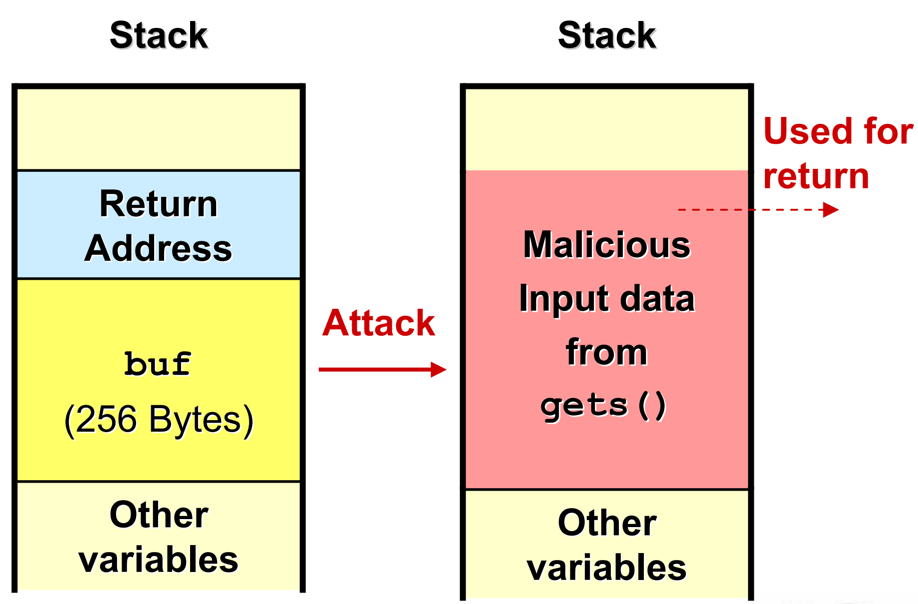
- Need to find common requirements for successful security exploits

Attack Model: Example - Stack Smashing

- Step 1. Inject malicious data through legitimate channels
  - Long input for buffer overflows
- Step 2. Bugs modify unintended memory locations
  - The data flows into `buf[]`, overwrites a return address
- Step 3. Take control over
  - Jump to injected target address (return address in the example)
  - Execute injected code

```
int func(void)
{
    char buf[256];

    while (gets(buf)) {...}
}
```



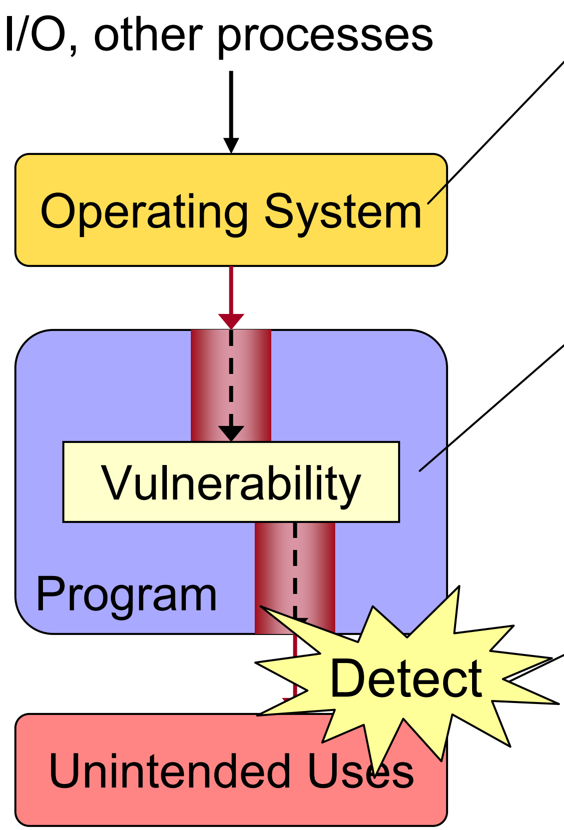
Observation: Common Requirements for Successful Attacks

- All attacks come from identifiable I/O channels
  - Both OS and applications explicitly manage I/O

- Malicious inputs should be used for a few security sensitive operations to take control of a process
  - Instructions: executes malicious code from I/O
  - Code pointers: arbitrarily redirect the control flow
  - Data pointers for stores: overwrite a critical program variable (valid_passwd = 1)

- In most applications, instructions and pointers usually do not come directly from I/O

Our Protection Scheme



Step 1. OS tags potentially malicious inputs as *spurious*

→ Security Tags;
0 – *authentic*,
1 – *spurious*

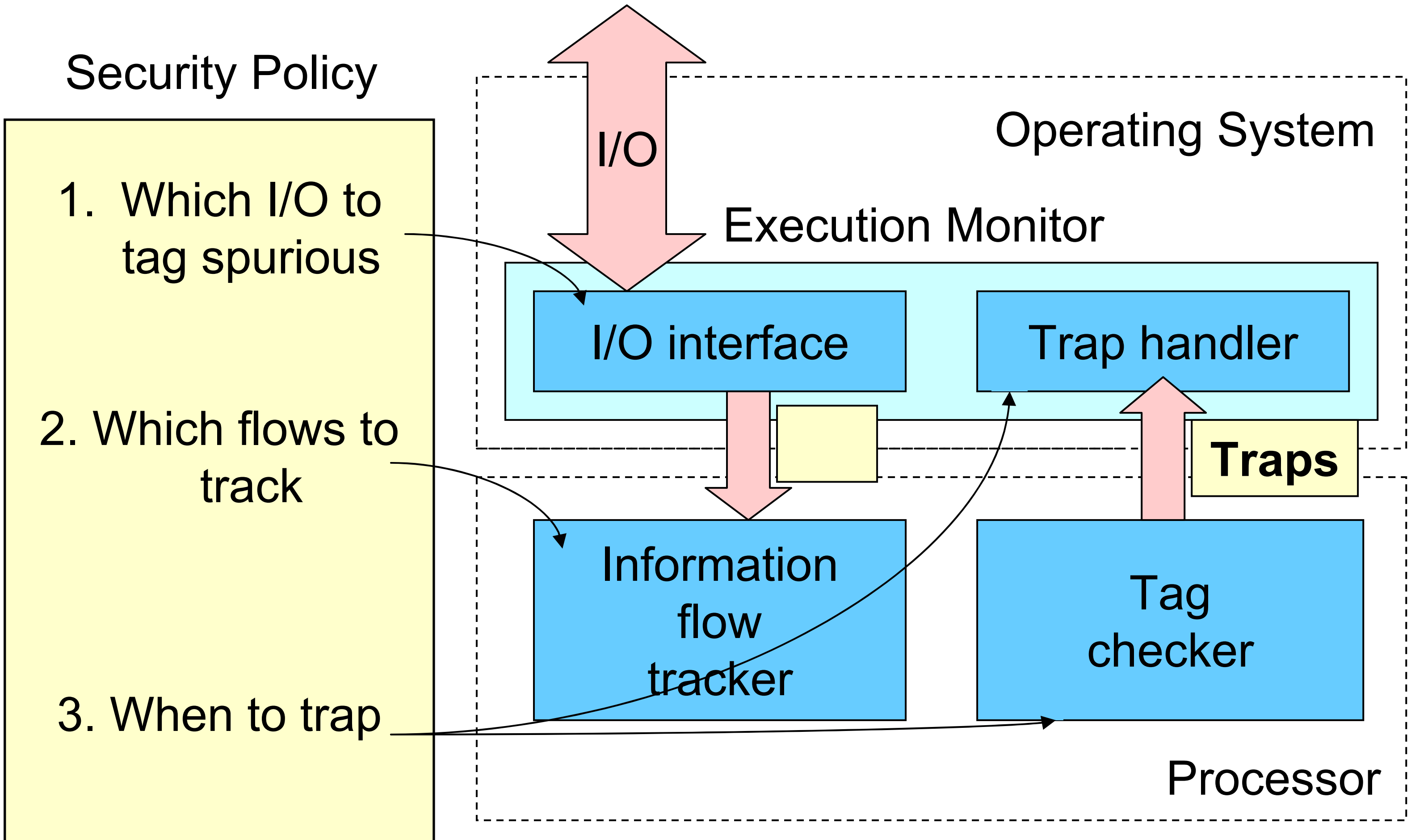
Step 2. Processors track the flow of the spurious values

→ Dynamic Information Flow Tracking

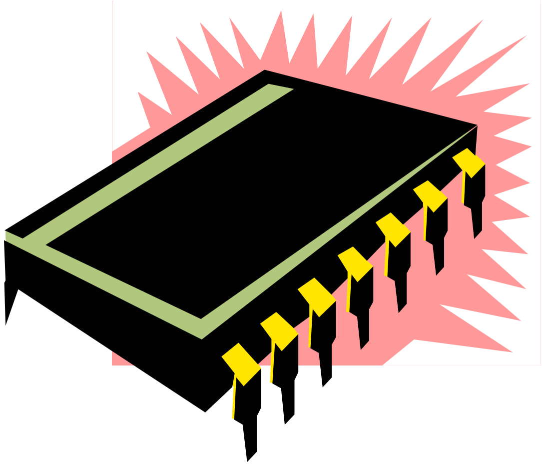
Step 3. Detect attacks
- Check and restrict the use of spurious values

→ Processors checks
+ trap handler

Implementation Overview



Architectural Support



Security Tags

- 1-bit information to indicate whether a piece of data can be trusted
  - 0 – *authentic*
  - 1 – *spurious*

- Granularity
  - One for each general purpose register (GPR)
  - One for each byte in memory – 12.5% overhead is a naïve management
  - Multi-granularity tags - Only 1.4% space overhead, 2.1% bandwidth overhead on average (based on experiments)

GPR (32 or 64 bits)	0/1		Memory (1 Byte)	0/1

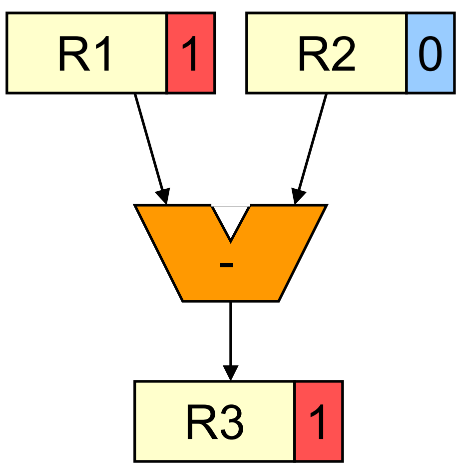
- At the start-up, all instructions and initial data will be tagged "authentic"
- During the execution, the execution monitor sets the tag for each I/O input according to the security policy

Dynamic Information Flow Tracking

- Compute a new security tag for each operation
  - If *spurious* data controls a result, the result is also *spurious*
- Various types of dependencies exist
  - Direct copy: load/store spurious data
  - Computation: compute from spurious data
    - Pointer additions
    - Other computations
  - Load address: load from spurious address
  - Store address: store into spurious address
- Propagation Control Register (PCR) determines which dependencies to track
  - Execution monitor sets the register based on the security policy

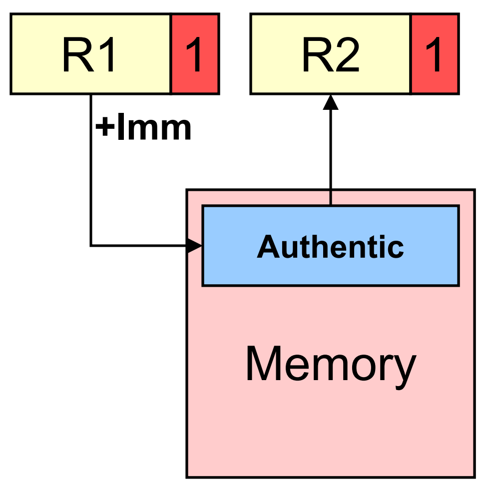
Security Tag Computation Examples

SUB R3, R1, R2



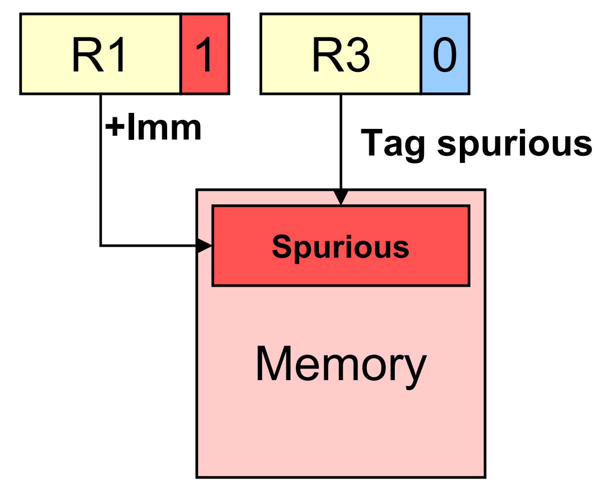
T[R3] =
T[R1] OR T[R2]

LD R2, Imm(R1)



T[R2] =
T[MEM] OR T[R1]

ST R1, Imm(R2)



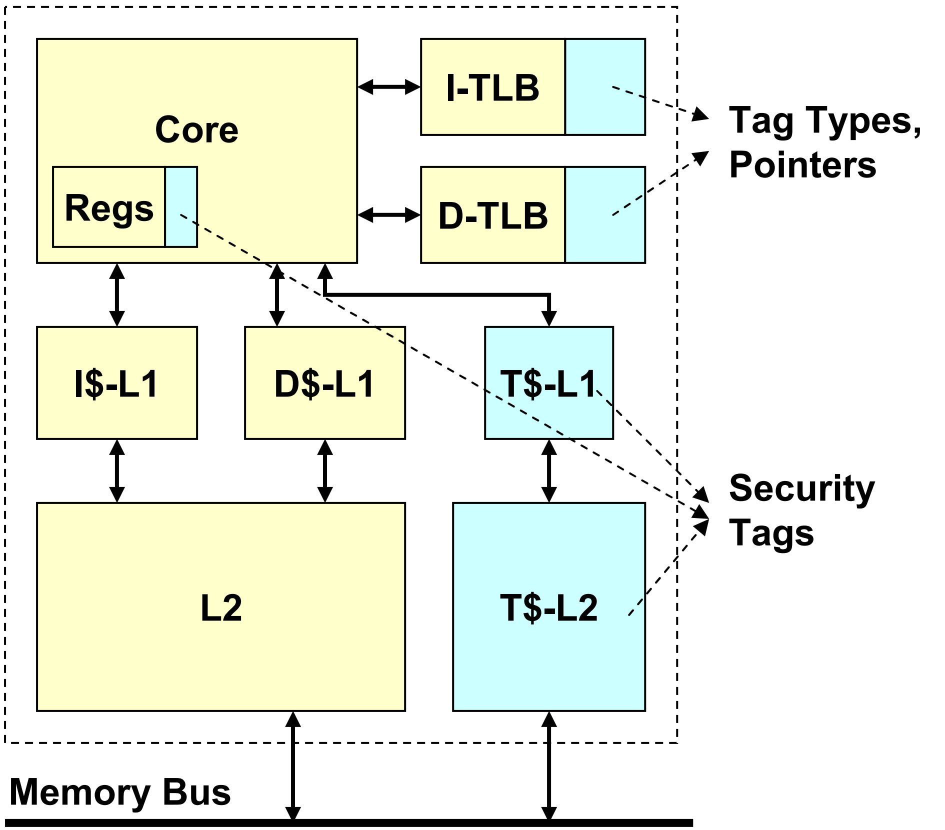
T[MEM] =
T[R3] OR T[R1]

Tag Checker

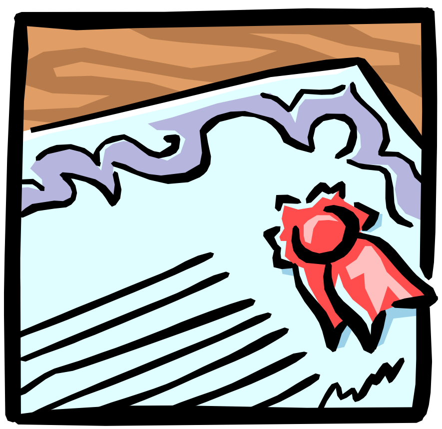
- Processor traps when spurious values are used for sensitive operations
- Sensitive values to be checked
  - Instructions
  - Load addresses
  - Store addresses
  - Jump target addresses
- Trap Control Register (TCR) determines which uses of spurious values generate a trap

Hardware Support Summary

- 1-bit tag for each GPR
- Small modification to ALU
  - Tag computation (logical OR)
- TLB contains tag types and tag pointers
- Separate tag caches
  - Allow parallel accesses to data and tags
  - Exploit multi-granularity tags
    - Tags will be often less than 1/8 of data



Security Policy



Security Policy

- Defines "spurious" values
  - I/O channels to be tagged
  - Dependencies to be tracked
- Defines illegal uses of spurious values
  - Trap conditions
  - Software checks in the handler
- Can be general for many programs, or customized for each program

Take 1: Maximum Security

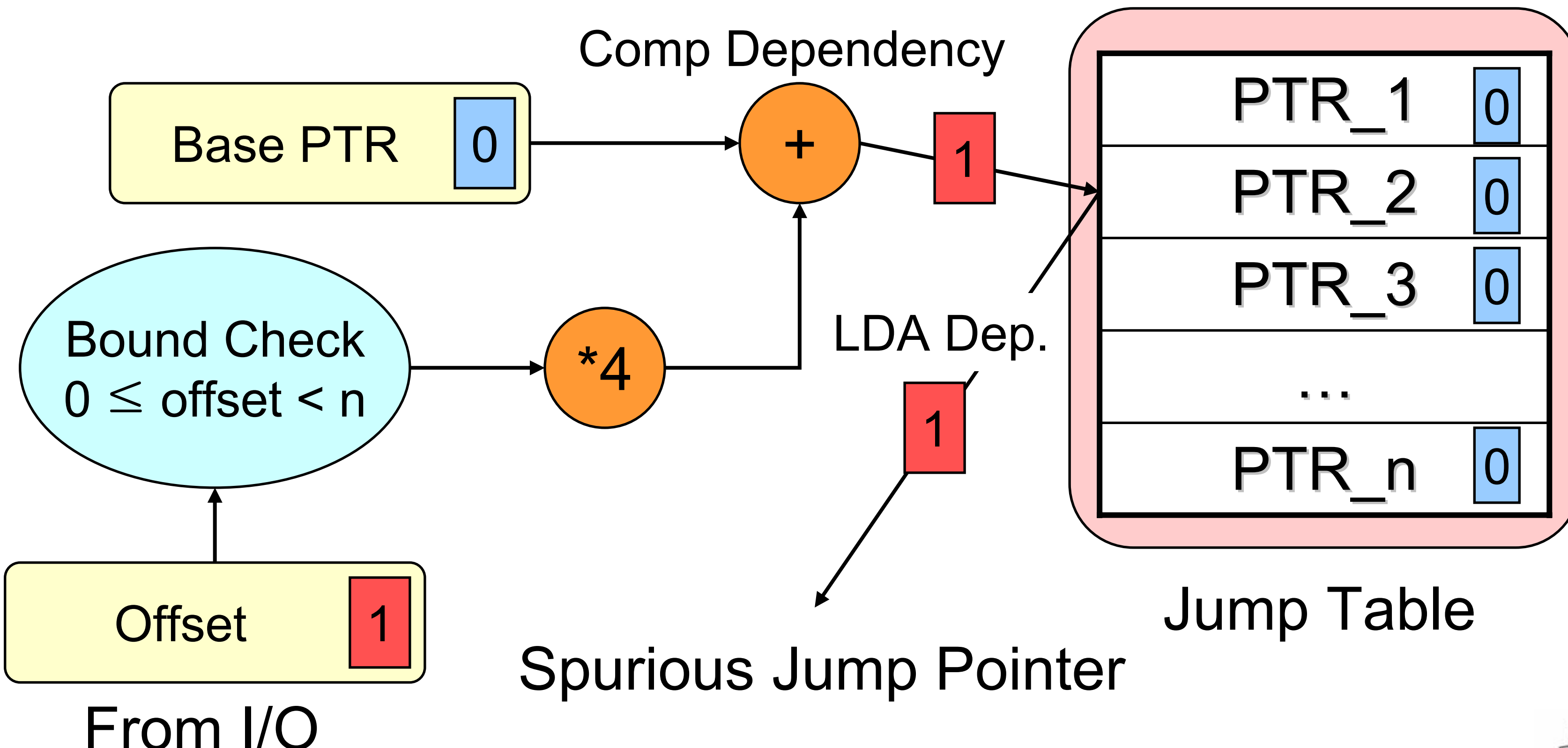
- Untrusted I/O
  - ALL
- Tracked Dependencies
  - ALL
- Trap Condition
  - Instruction
  - Jump target address
  - Store address
- Trap Handler
  - Terminate the process

False alarms from spurious pointers

Need to balance security and false positives

Where Are Spurious Pointers From?

- I/O inputs are often used as offsets for pointer tables after a bound check



Take 2: Allow Legitimate Uses

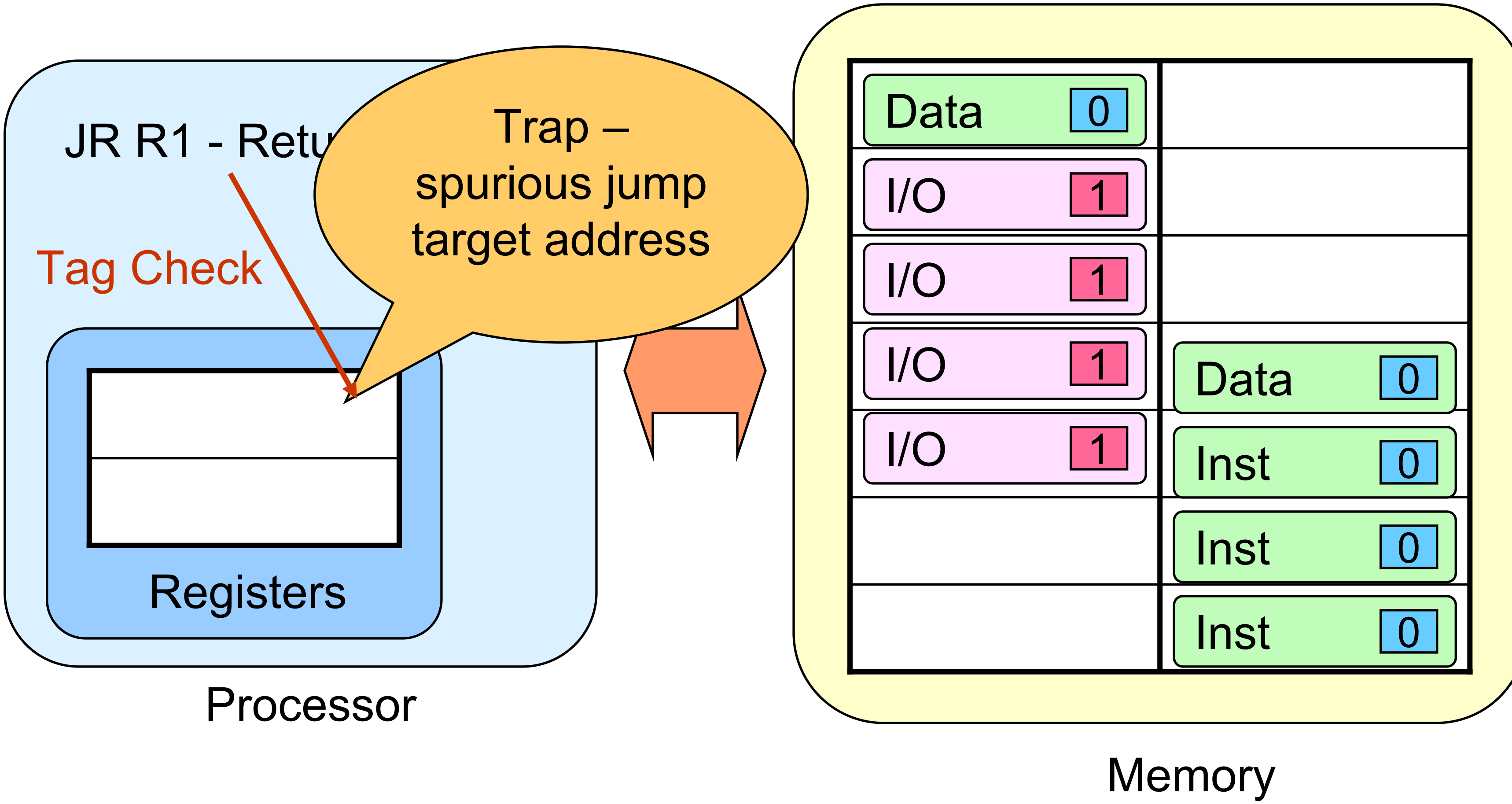
- Unstrusted I/O
  - ALL
- Tracked Dependencies
  - ALL but pointer offsets
- Trap Condition
  - Instruction
  - Jump target address
  - Store address
- Trap Handler
  - Terminate the process

For pointer additions such as [4*r1+r2] in x86, s4addq r1, r2, r3 (r3 ← r2+4*r1) in Alpha

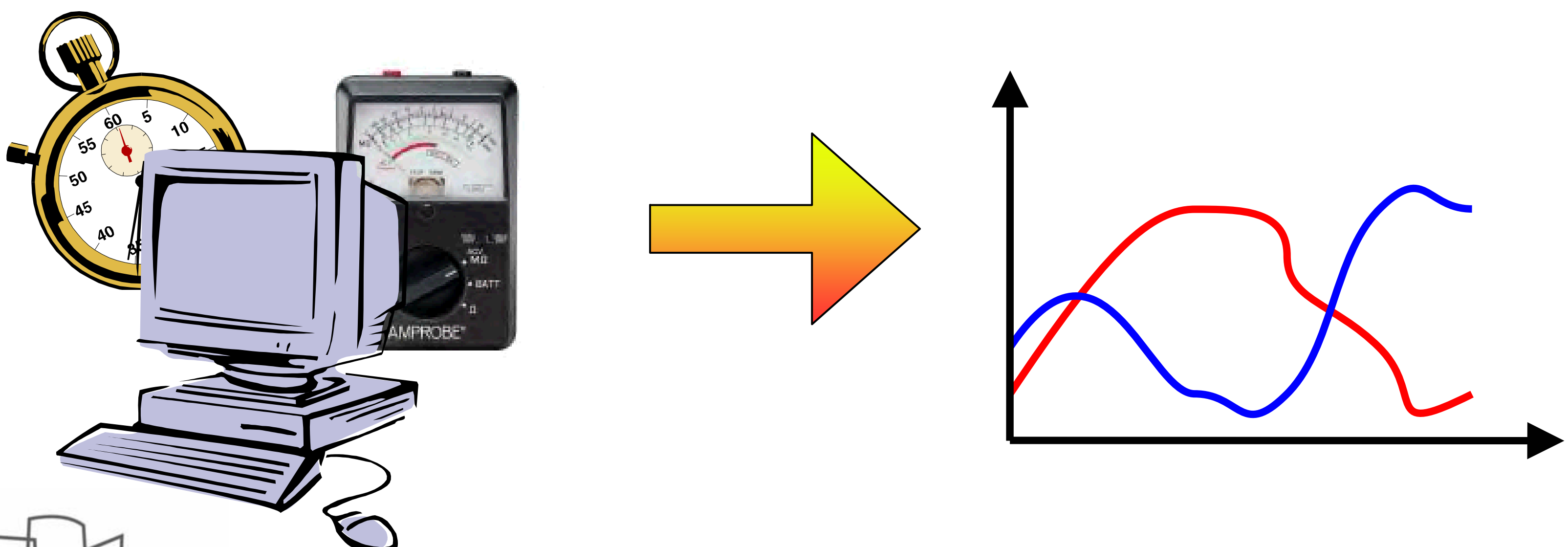
The new tag = T[r2]

assuming the bound check is done.

Example – Stack Smashing



Evaluation



Simulation Frameworks

- Bochs (Intel x86)
  - Keyboard and network I/O are tagged spurious
  - Used to evaluate the effectiveness of our scheme
  - x86 applications on Debian Linux (3.0r0)
- SimpleScalar (Alpha)
  - All I/O are tagged spurious
  - sim-fast: functional evaluations (false alarms, space overheads for tags)
  - sim-outorder: performance evaluations
  - SPEC CPU2000 benchmarks

Detecting Security Attacks

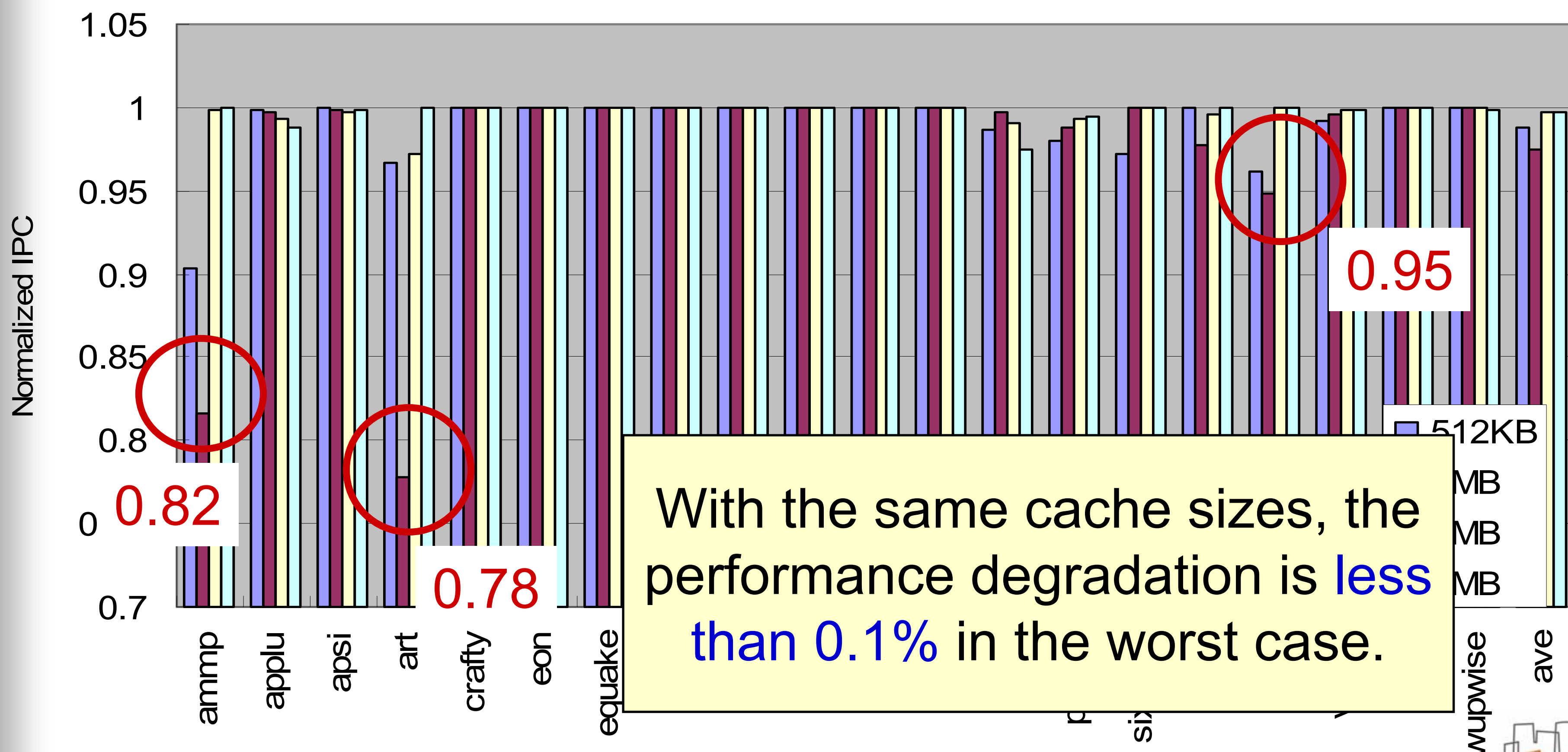
- Buffer overflow testbed (by Wilander, 2003)
  - Covers all 20 combinations possible in practice
    - Overwrite technique: direct, pointer redirection
    - Buffer location: stack, heap/BSS/data
    - Attack targets: return address, base pointer, function pointer, and longjmp buffers
  - The best protection scheme in 2003 detected only 50%
- Format string attacks (from TESO security group)
  - Overflow a buffer or use %n conversion specification
- Detects and stops ALL security attacks tested
  - So far, all known attacks directly inject pointers or instructions → lenient tag propagation does not matter

No False Alarms

- Common x86 applications
  - Debian Linux 3.0 (keyboard, network marked spurious)
  - System commands: ls, cp, vi, ping, etc.
  - openSSH server/client
- Dynamically generated code
  - A simple http server (TinyHttpd2) – marked spurious
  - SUN's JAVA SDK 1.3 HotSpot VM with JIT
- SPEC2000 CPU benchmarks
  - Input files are marked spurious

Performance Degradation

- Various L2 sizes with 1/8 tag caches – 1.1% degradation on average
  - Pessimistic overhead: baseline case gets 12.5% larger caches if it helps



Conclusion

- Dynamic information flow tracking provides a powerful tool for system security
  - Tells whether a value came from untrusted I/O or not
  - Can restrict the use of potentially malicious input values
- Our protection scheme is effective against large class of attacks
  - Stops both buffer overflow and format string attacks
  - No false alarms for real-world applications
- The overhead of tagging can be small
  - 1.4% space, 2.1% bandwidth, 1.1% performance overhead
- Many extensions are possible
  - Automatically identify bound checks and strictly follow dependencies
  - Combine with static analysis
  - Other applications such as protecting private information or debugging

Questions?

- Our website

  http://www.csg.csail.mit.edu

- Contact Info

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