Data Space Randomization (DSR)

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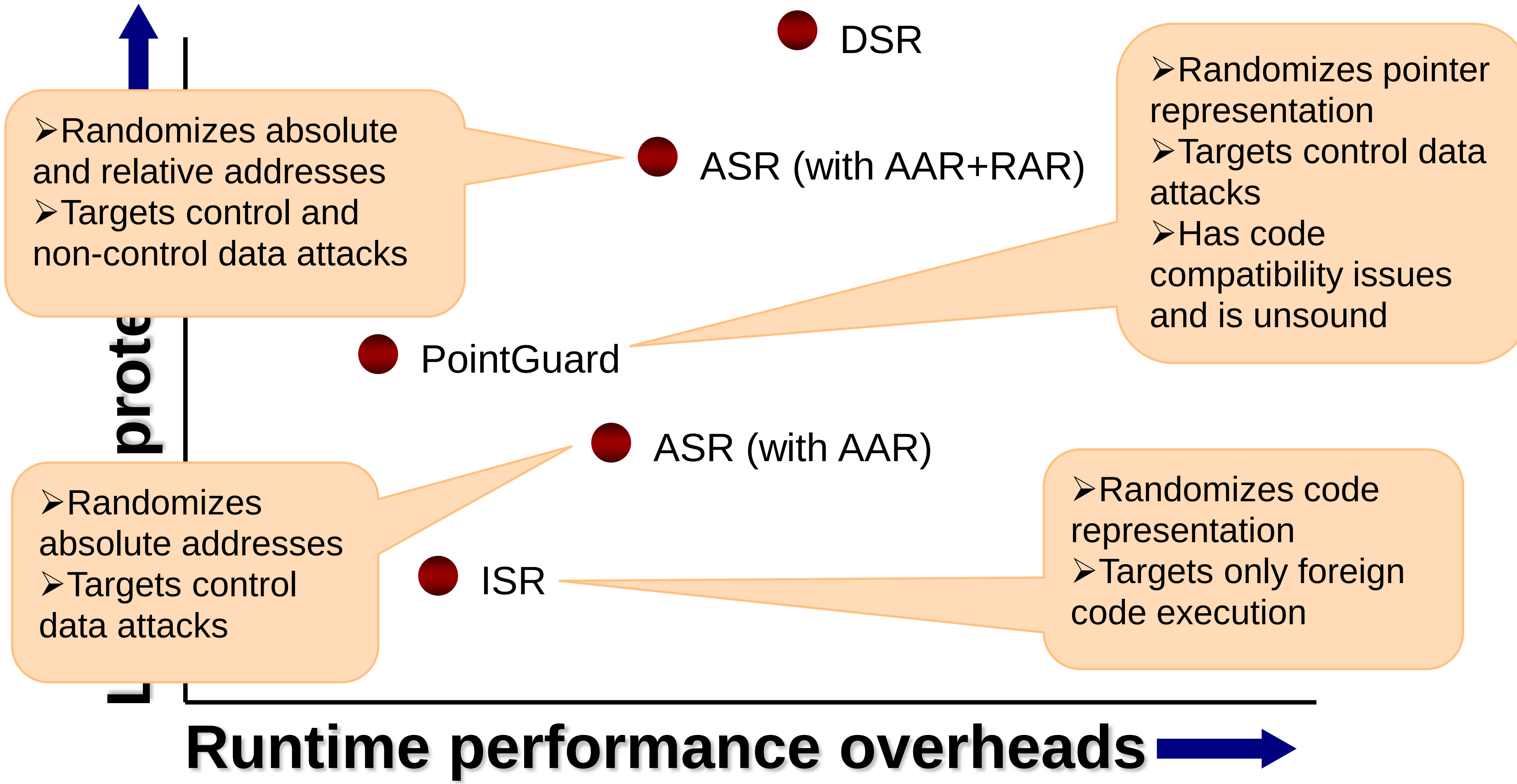
Importance of Memory Error Exploits

- Memory error exploits continue to be the dominant threat
  - Behind most “critical updates” from Microsoft and other vendors
  - Mechanism of choice in “mass market” attacks, including worms
- Defense techniques to address this problem continues to be the hot topic of research
  - Over 20 techniques have been invented so far
  - Techniques that provide full protection haven’t been practical
    - High performance cost
    - Code compatibility issues
  - Diversity based defenses emerging as more promising
    - Address Space Randomization (ASR)
    - Instruction Set Randomization (ISR)

Previous Diversity Based Techniques

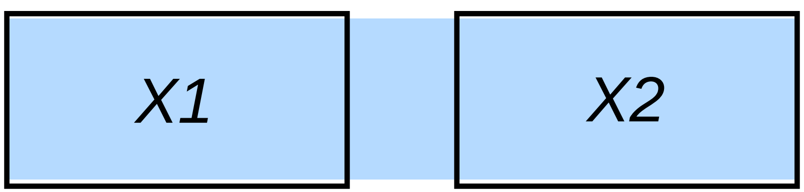


RAR: Relative Address Randomization

AAR: Absolute Address Randomization

DSR Technique

- **Basic idea**: randomize data representation
  - Xor each data object with a *distinct random mask*
  - Effect of data corruption becomes non-deterministic
    - **Example**: use out-of-bounds access on array ***X1*** to corrupt variable ***X2*** with value ***V***
      - Actual value written: *mask*(***X1***) ⊕ ***V***
      - When ***X2*** is read, its value interpreted as *mask*(***X2***) ⊕ (*mask*(***X1***) ⊕ ***V***)
      - *mask*(***X2***) ⊕ *mask*(***X1***) ⊕ ***V*** **≠** ***V*** (because *mask*(***X2***) **≠** *mask*(***X1***))



Example: Buffer overflow

Differences with PointGuard

- DSR randomizes all data objects, not just pointers
- PointGuard breaks working programs, DSR doesn't
- Attacks targeted:
  - PointGuard targets *absolute address-dependent attacks* (pointer corruption)
  - DSR targets *relative address-dependent attacks*
    - Helps defeating non-control data attacks that corrupt files names, userids, command names, authentication data, …
    - Automatically defeats absolute address-dependent attacks as pointer corruption step is relative address-dependant
- Unlike PointGuard, DSR is not vulnerable to *information leakage attacks* (details forthcoming)

DSR Transformation Approach

- For each variable ***v***, introduce another variable ***m_v*** for storing its mask
- Randomize values assigned to variables (LHS)
  - Example: ***x = 5*** ➡ ***x = 5; x = x ^ m_x;***
- Derandomize used variables (RHS)
  - Example: (***x + y)*** ➡ ***((x ^ m_x) + (y ^ m_y))***
- Key problem: aliasing

```
int x, y, *ptr; …
ptr = &x; …
ptr = &y; …
z = *ptr
```

  - Unfortunately, we cannot statically determine the mask associated with ****ptr*** – it could be that of ***x*** or ***y***

Aliasing Problem

- **Solution to aliasing problem**: assign the same randomization mask to possibly aliased objects
  - Requires *alias analysis*
  - Current implementation supports Steensgaard's algorithm for alias analysis
    - Flow-insensitive
    - Context-insensitive
    - Field-insensitive
    - All heap objects allocated at the same point represented by a single logical object
    - Linear time complexity

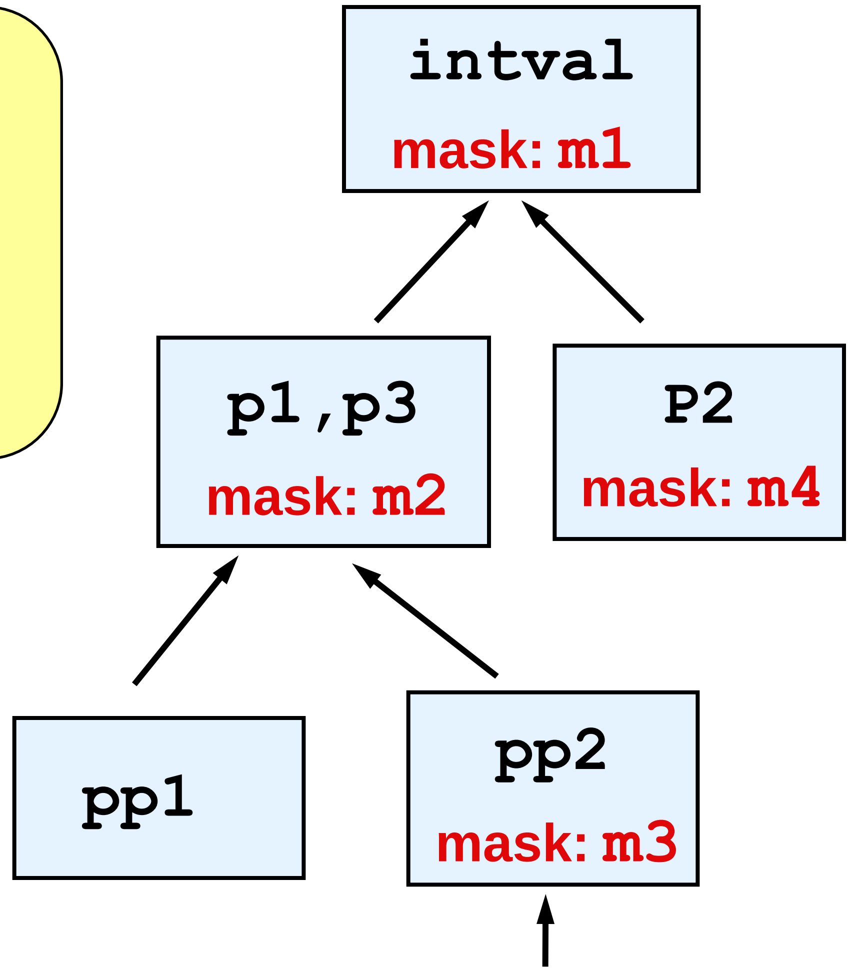
Pointer Analysis & Mask Assignment

```
int intval;
```

```
p2 = *pp2

p2 = *(pp2^m3)^m2;
p2 = pp2^m4;
```

```
p          &p1;...
pp         &p3;...
pp2     pp1;
p2   = *pp2;
...
     = &pp2;
```



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Optimization

- **Basic idea**: mask only *overflow candidate objects (OCOs),*

  e.g., arrays, structures containing arrays, objects whose addresses are taken

  - Optimization is very effective because majority of memory access in a typical program are to non-OCOs
- Ensure that optimization doesn't significantly impact security
- Claim: all data corruptions involve overflows from OCOs
  - All relative address-dependent attacks involve overflows from OCOs
  - All absolute address-dependent attacks involve corruption of pointers
    - Require a relative address-dependent step, e.g., buffer overflow, integer overflow, heap overflow, etc.
- Implication: need protection from overflows in OCOs

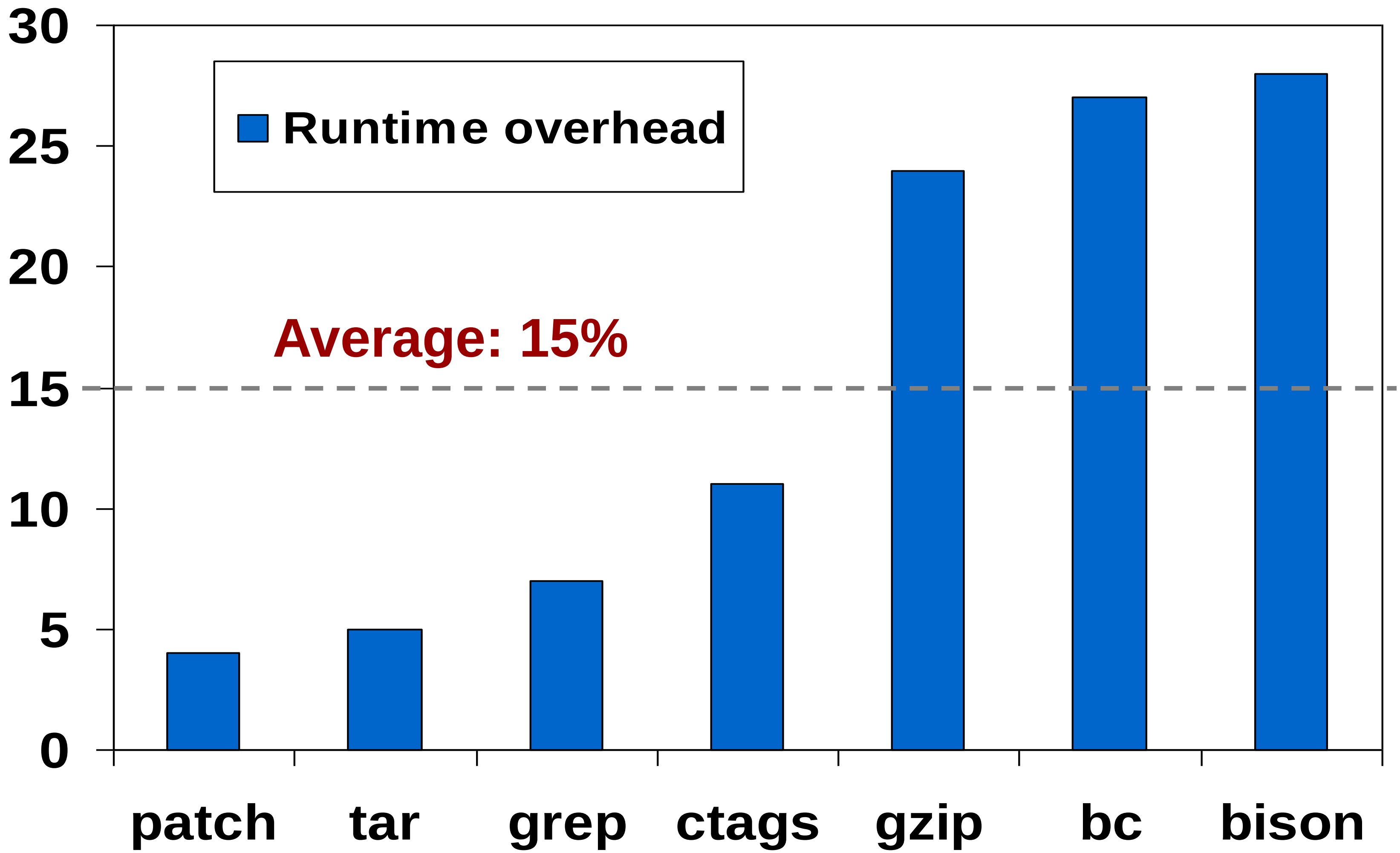
Protection from Overflows in OCOs (Optimization ctd)

- Protect non-OCOs from overflows in OCOs
  - Non-OCOs separated from OCOs with an unmapped memory page
- Guard against overflows among OCOs
  - Use of distinct masks provides automatic protection for overflows between unaliased OCOs
  - Prevent overflows between aliased OCOs by allocating them in disjoint memory regions
    - Stack: allocate local OCOs on disjoint stacks (buffer stacks) if small in number; allocate in heap if the number is high
    - Static: number of disjoint memory areas statically known
    - Heap: heap OCOs allocations (typically large in number) randomly distributed in a fixed number of heap memory regions

Implementation

- Based on source-to-source transformation of C programs
  - Uses CIL as front-end and OCAML as implementation language
- Implementation issues
  - Handling overflows within structures
    - Use field-sensitive pointer analysis so as to assign distinct mask to each field of a structure (not done yet)
    - Handle functions such as memcpy, bzero in a context-sensitive way
  - Handling variable argument functions
    - Treat them as if they take array (with maximum size limit) parameter
  - Transformation of libraries
    - Source code available: need dynamic mask resolution
    - Source code unavailable: need summary functions for library calls

Execution Time Overheads



Effectiveness Against Various Attacks

- Stack buffer overflows
  - Overflows to corrupt data on main stack (e.g., return address, based pointer, saved registers) fail
  - Overflows among overflow candidate objects
    - fail if source and target objects are in different buffer stack or disjoint memory regions
    - succeed with probability 2^{-32} otherwise
- Static buffer overflows
  - Overflows to corrupt non overflow candidate objects fail
  - Overflows between overflow candidate objects
    - fail if source and target objects are in different memory regions
    - succeed with probability 2^{-32} otherwise

Effectiveness Against Various Attacks

- Heap overflows
  - Traditional attack (corruption of heap control data) succeeds with probability 2^{-32}
  - An overflow from one heap block to the next succeeds with probability > 2^{-32} (property of a program)
    - Heap objects randomly distributed
    - Nonetheless, such overflows also detected when control data between the heap blocks get corrupted
- Format string attacks
  - Traditional attack with **`%n`** directive fails
  - DSR cannot stop attacks that print contents of stack with **`%x`**
- Relative address attacks based on integer overflows
  - If source and target objects share the same mask, such attacks can be successful (protection provided in the form of RAR)

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Effectiveness Against Attacks targeting DSR

- Information leakage attacks
  - If a masked data is leaked, an attacker can deduce the mask if the plaintext data value is known
  - Attempt to read masked data results in reading plaintext data
- Brute force and guessing attacks
  - become difficult because of low probability of success
- Partial pointer overwrites
  - become impossible on stack-resident data because the main stack does not contain overflow candidate objects

Related Work

- Runtime guarding: StackGuard, StackShield, RAD, Libsafe, Libverify, ProPolice, FormatGuard, …
  - Attack specific, no comprehensive protection
- Runtime bounds and pointer checking: [Austin+94], [Jones+97], Cyclone, CCured, [Ruwase+04], [Xu+04], [Dhurjati et al 06]
  - High overheads or incompatibility with legacy code
- Runtime enforcement of static analysis results: CFI, DFI, WIT
  - Don’t target all exploits (e.g., data leakage/corruption)
- Randomization techniques: ASR (PaX, [Bhatkar+03], [Xu+03]), ISR ([Barrantes+03], [Kc+03]), PointGuard
  - No or limited protection from non-control data attacks

Summary of Contributions

- Randomization of all types of data provides comprehensive coverage
  - Control data attacks
  - Non-control data attacks
- Unlike other randomization techniques, resistant to information leakage attacks
- Higher range of randomization than other randomization techniques
- Capable of detecting exploits that are missed by full bounds-checking techniques
  - Example: overflows within structures
- Low runtime overhead
  - Average around 15%

Thank You!

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