Efficient Pointer Integrity For Securing Embedded Systems

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COMPUTER SCIENCE

BROWN

Columbia University
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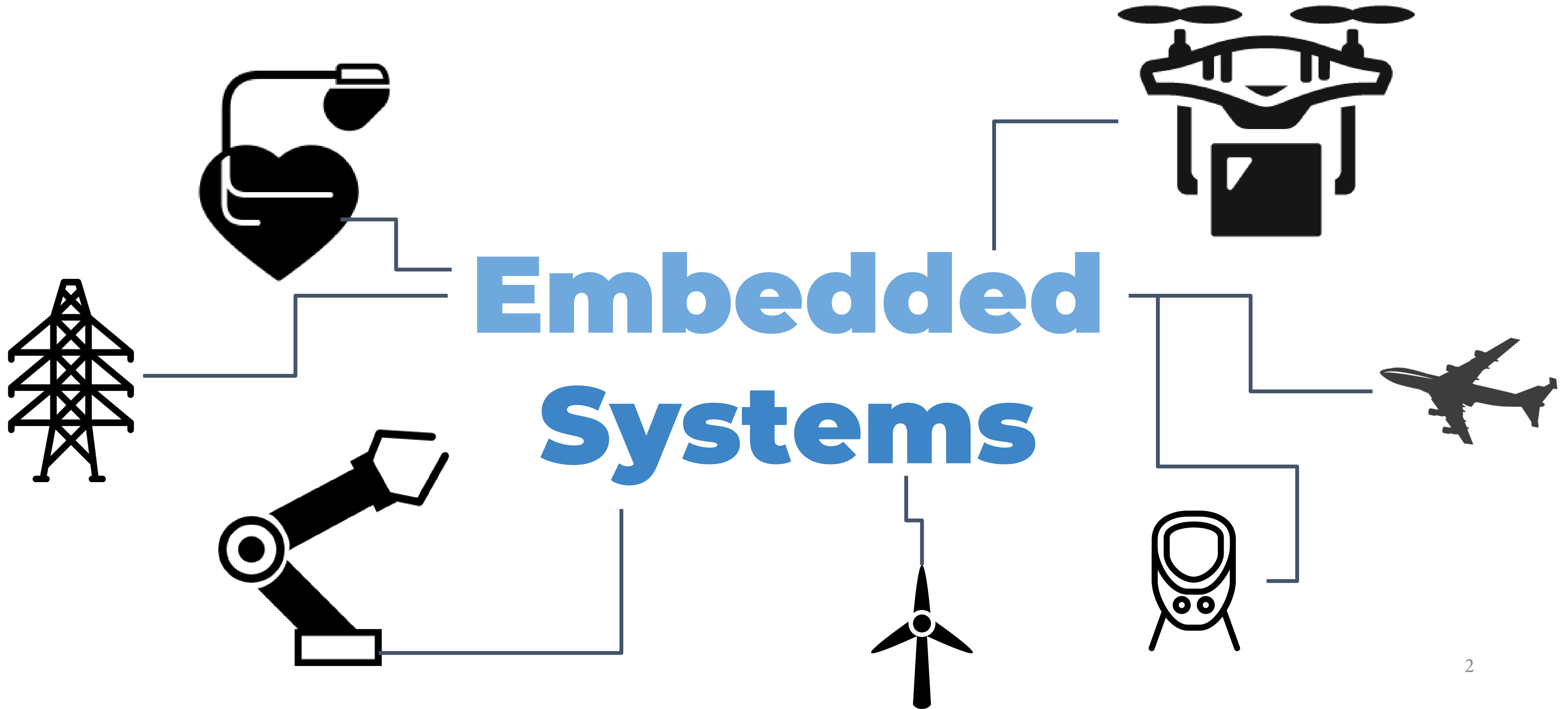
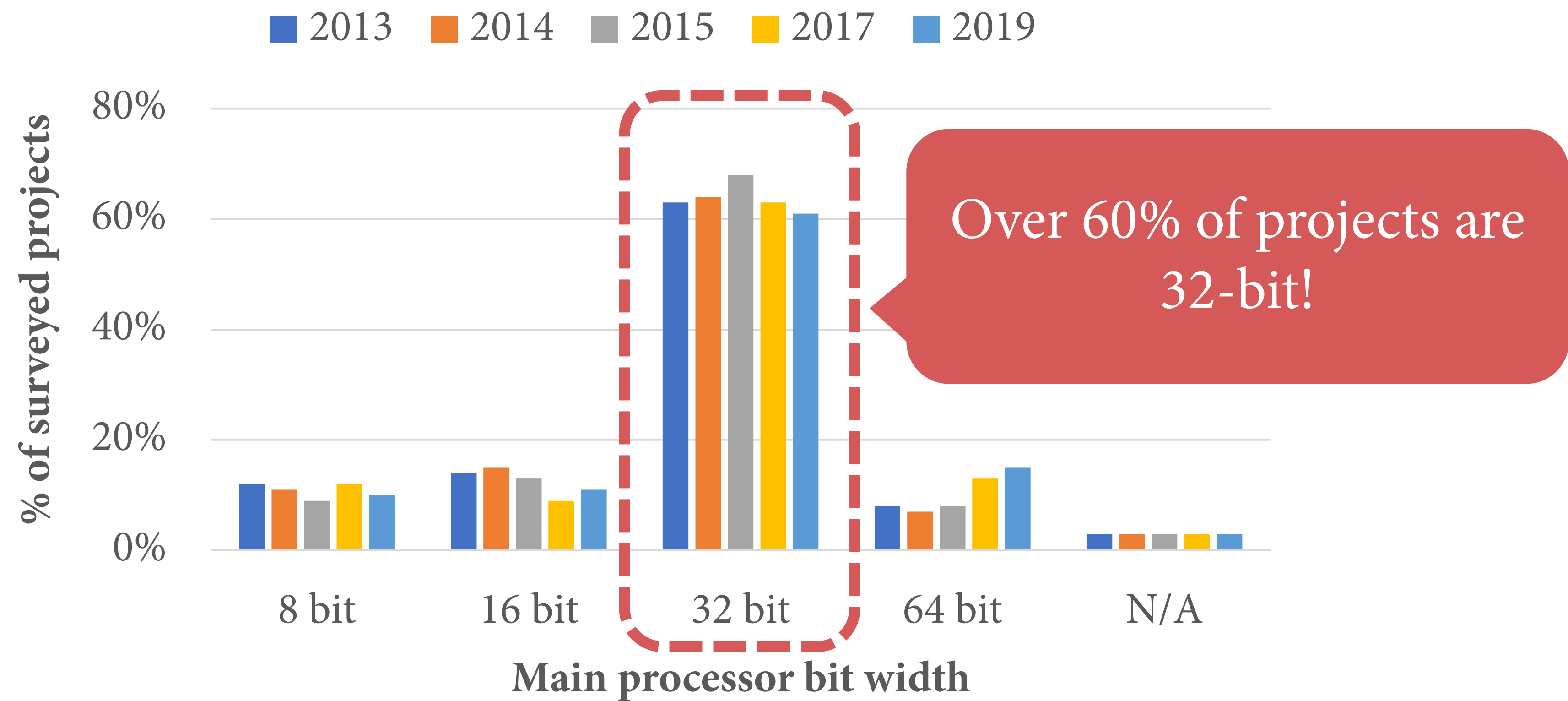
09/21/2021

Embedded systems are everywhere!

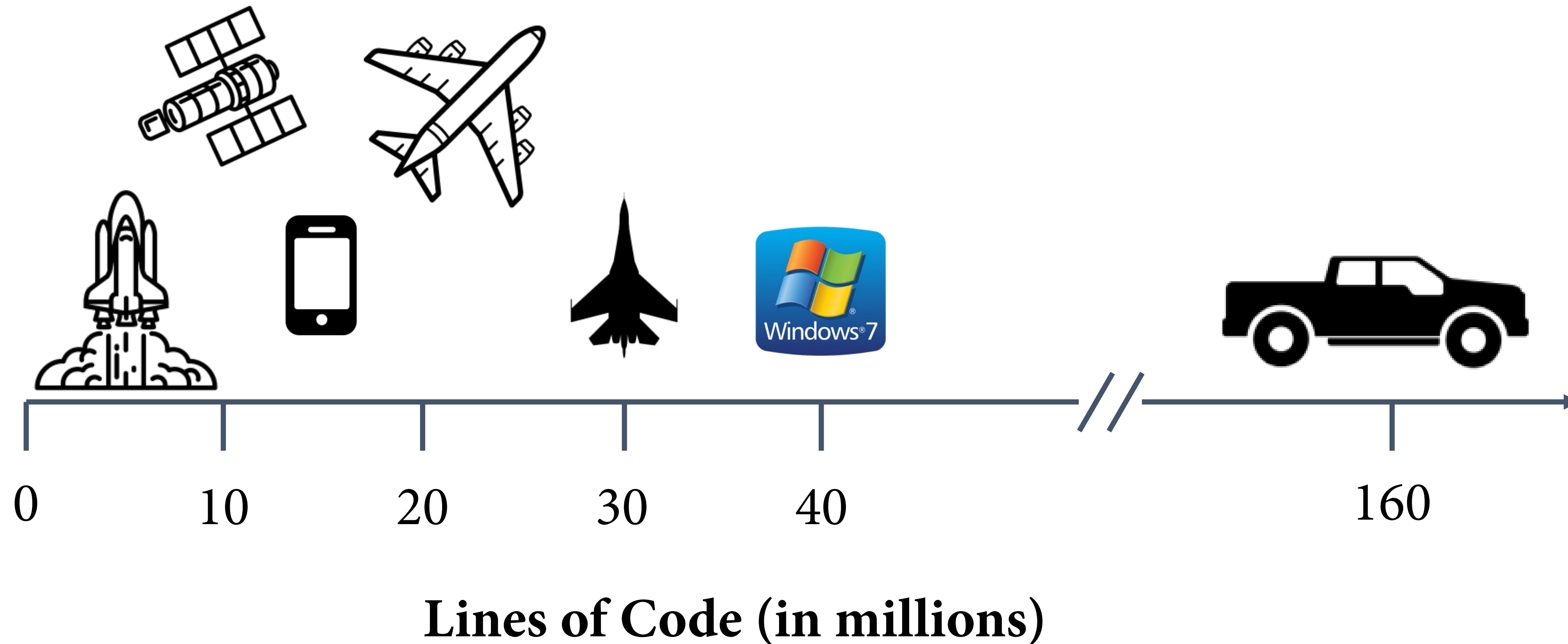


Embedded systems are dominated by 32-bit.



Why embedded system security is important?

Software has become increasingly complex.



Source: *http://bit.ly/KIB_linescode*

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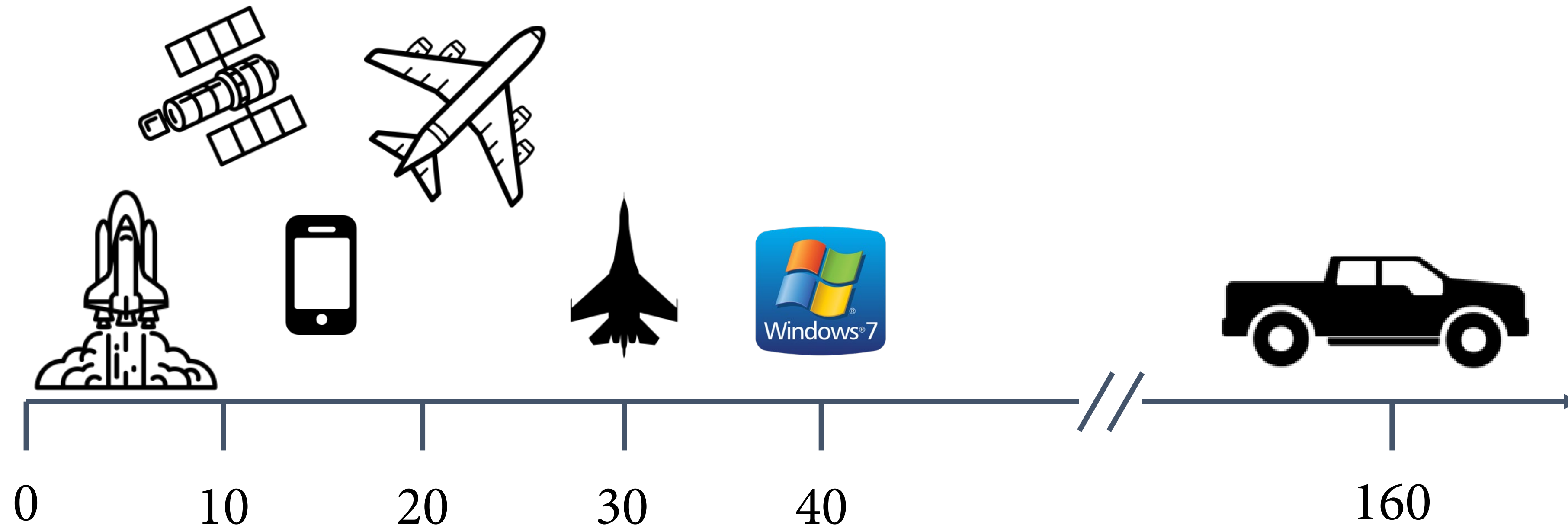

~~Lines of Code (in millions)~~

Number of Bugs

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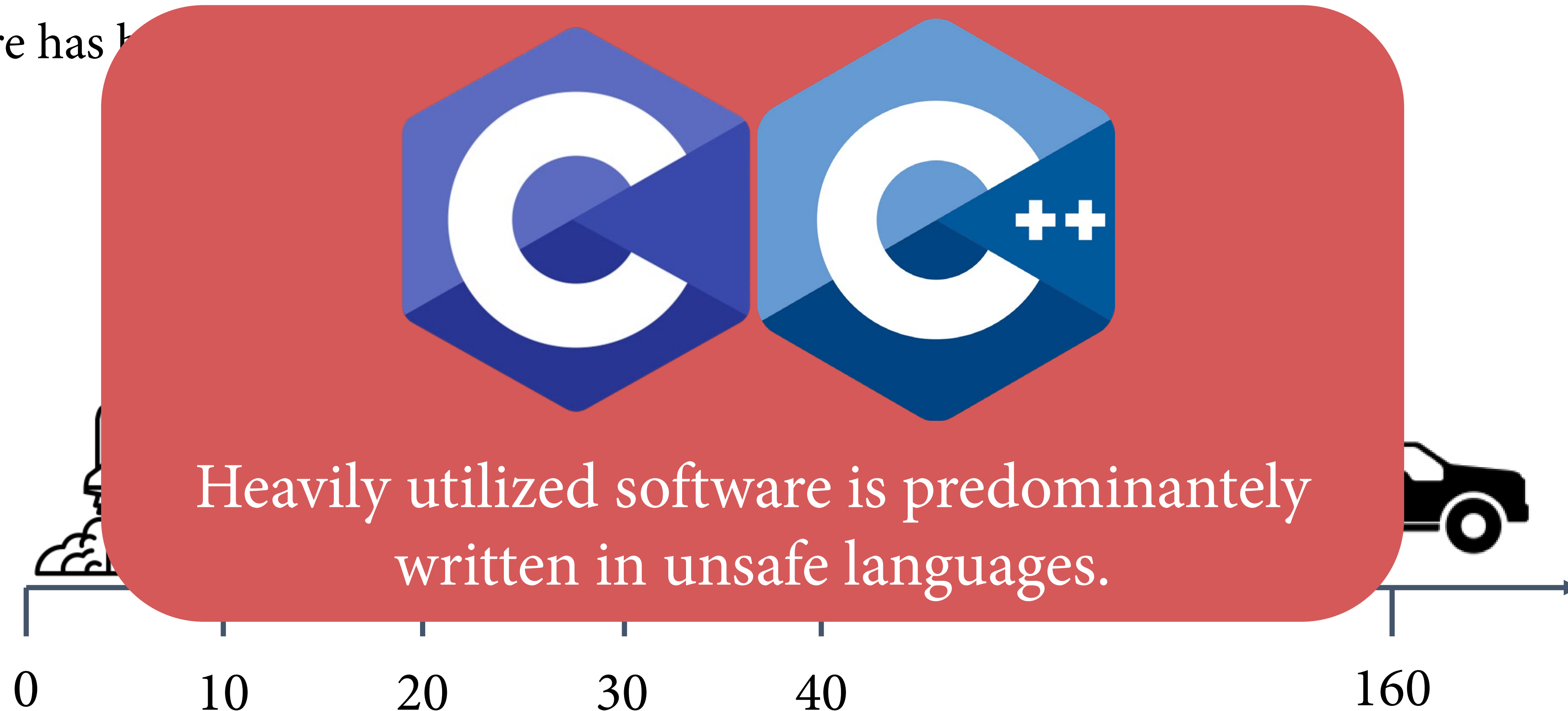

~~**Lines of Code (in millions)**~~

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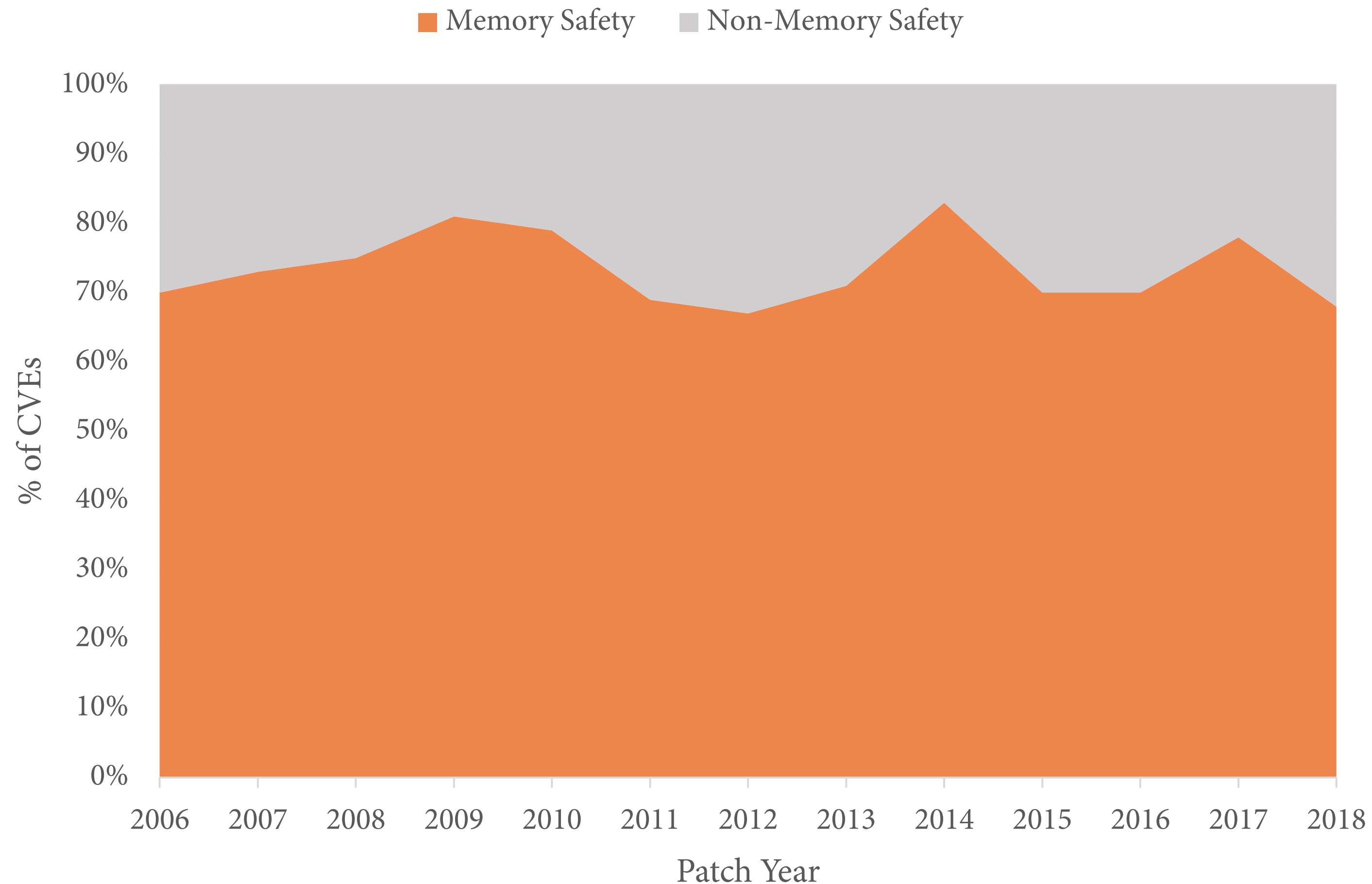
Source: *http://bit.ly/KIB_linescode*

Why Memory Safety?

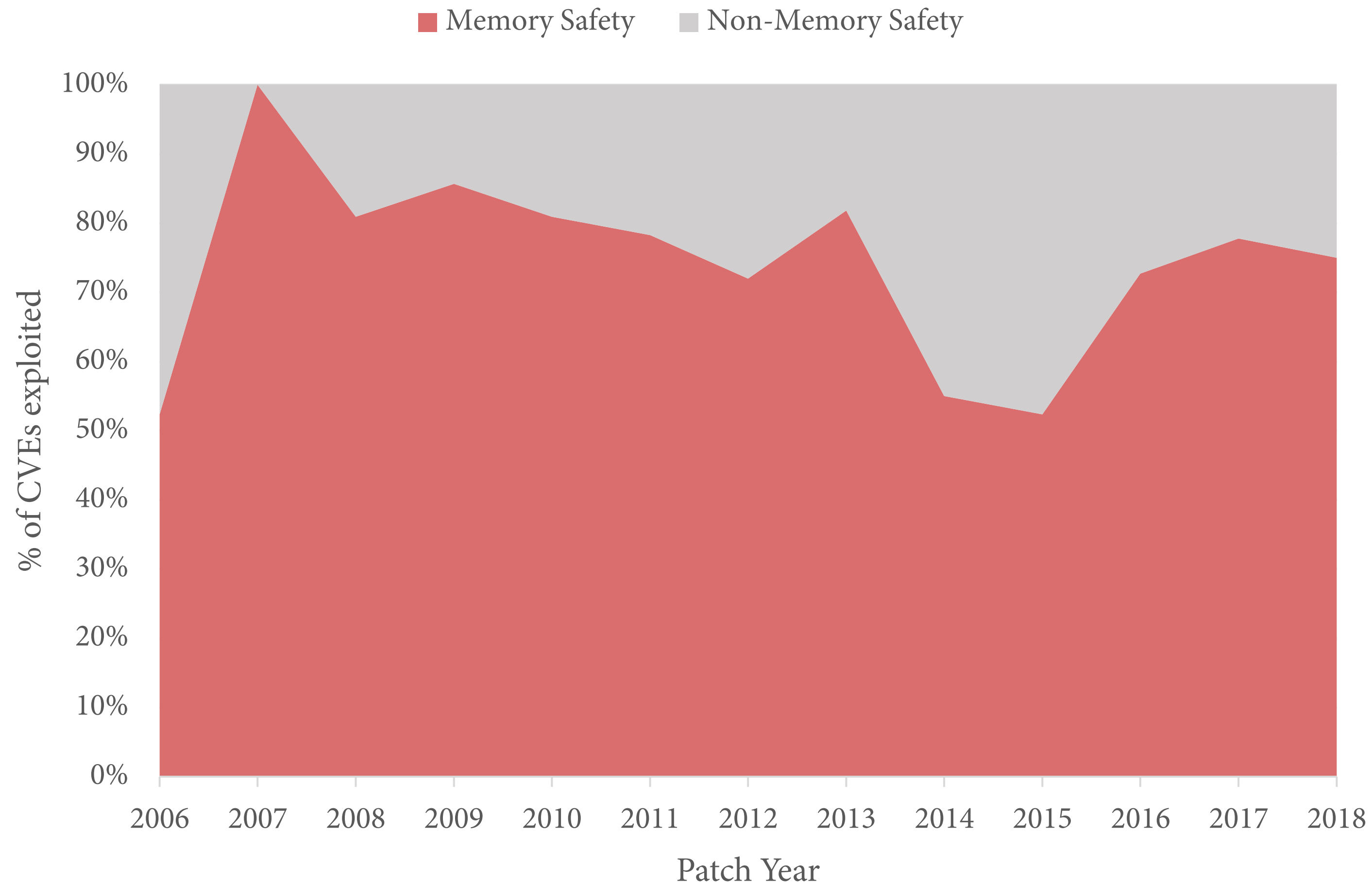
It is the predominant source of vulnerabilities (ie. CVEs).



Source: *Matt Miller, Microsoft Security Response Center (MSRC) - BlueHat 2019*

Why Memory Safety?

Memory Safety CVEs are heavily exploited.



***Source:** Matt Miller, Microsoft Security Response Center (MSRC) - BlueHat 2019*

EPI

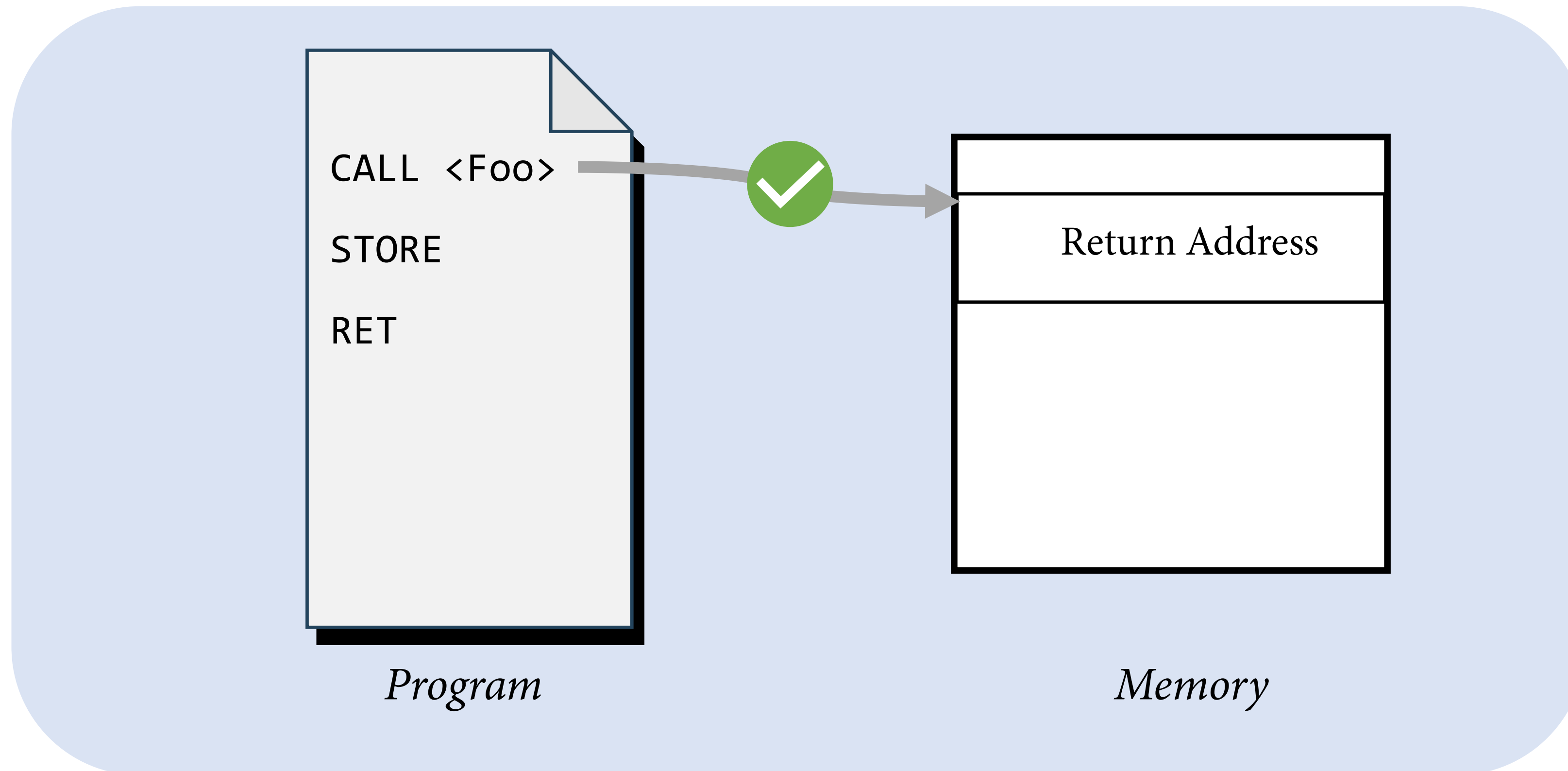
Return Address Integrity

```
CALL <Foo>

STORE

RET
```

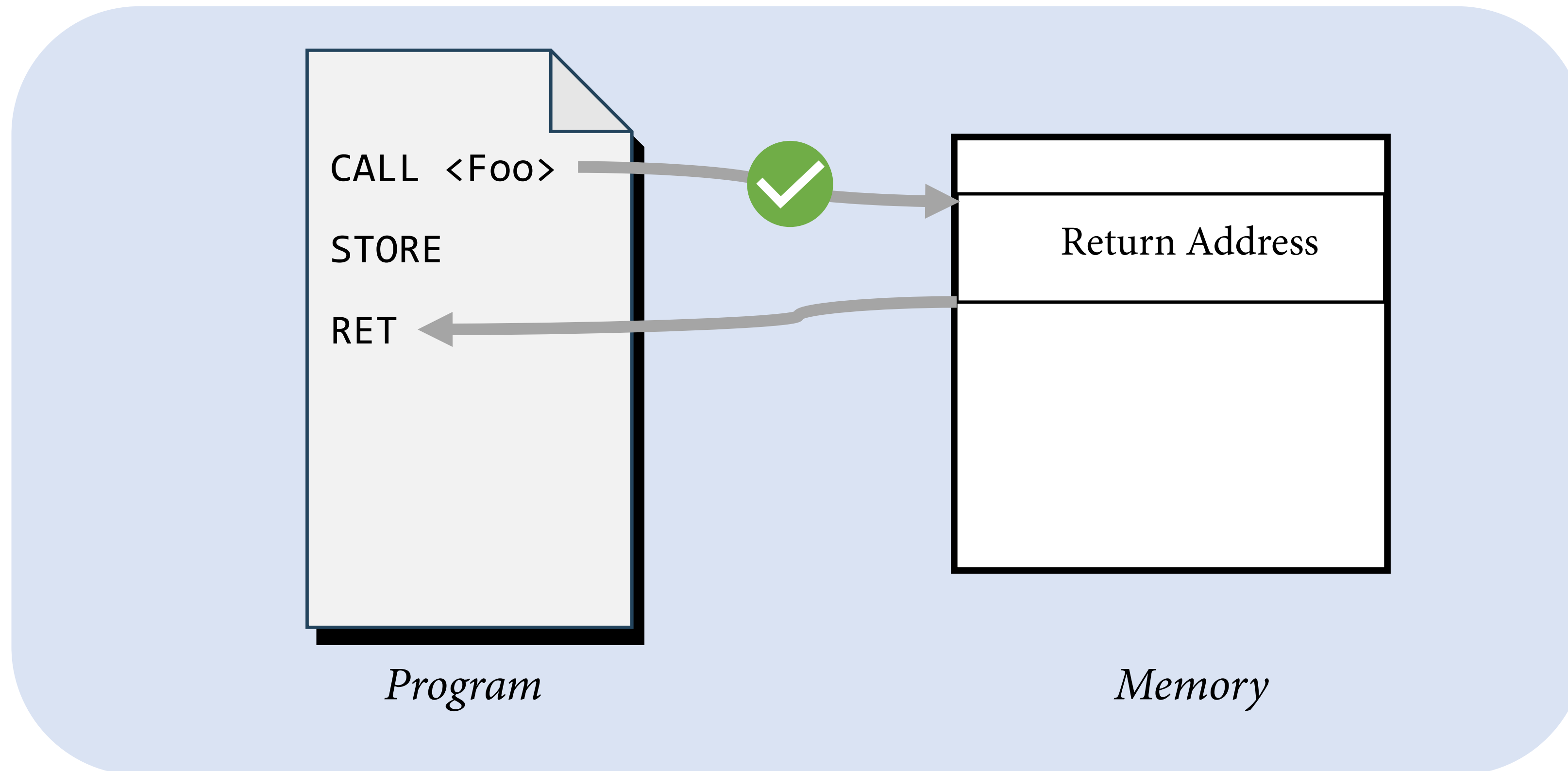
Program

Memory

Return Address Integrity



Return Address Integrity



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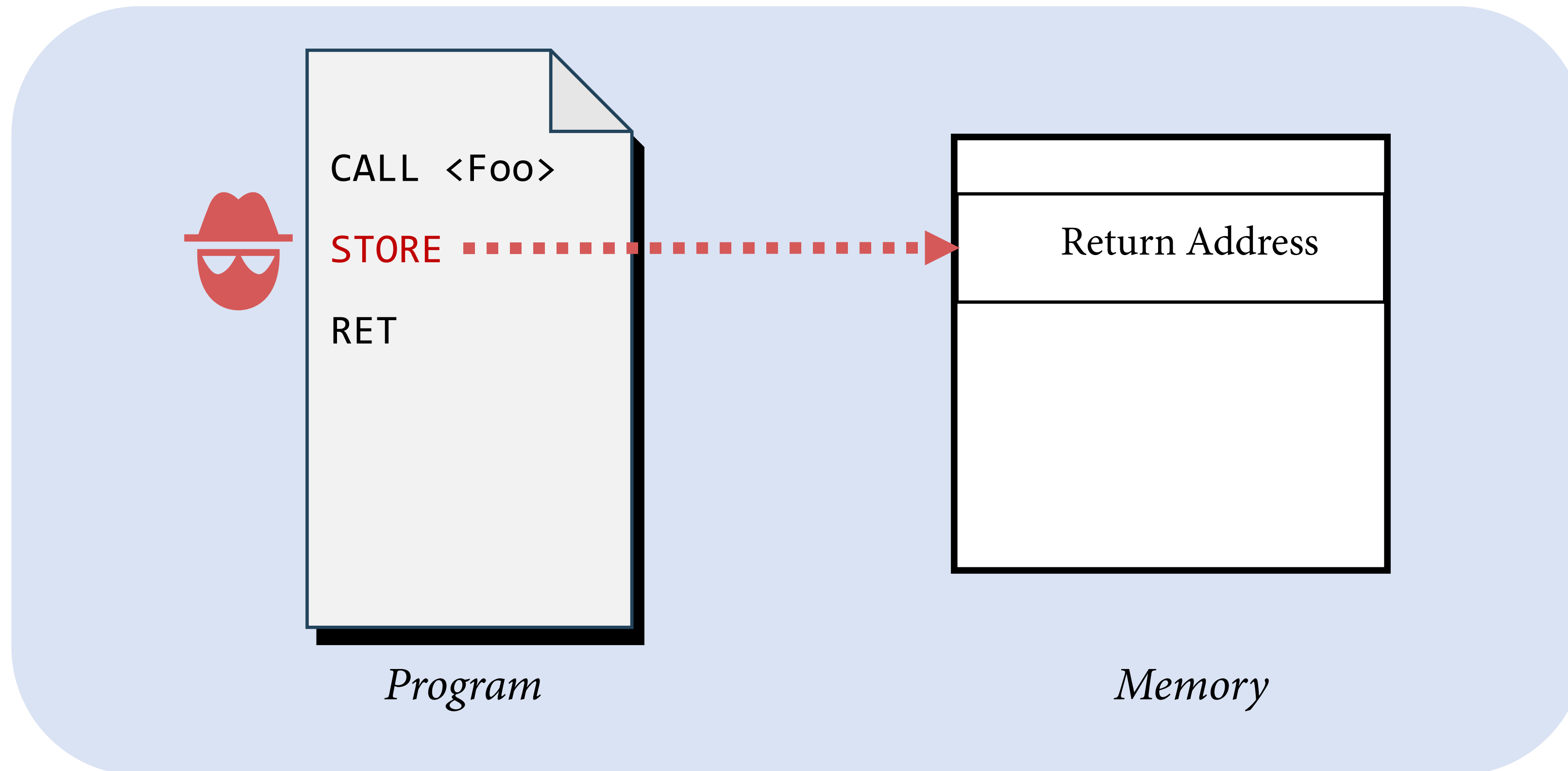

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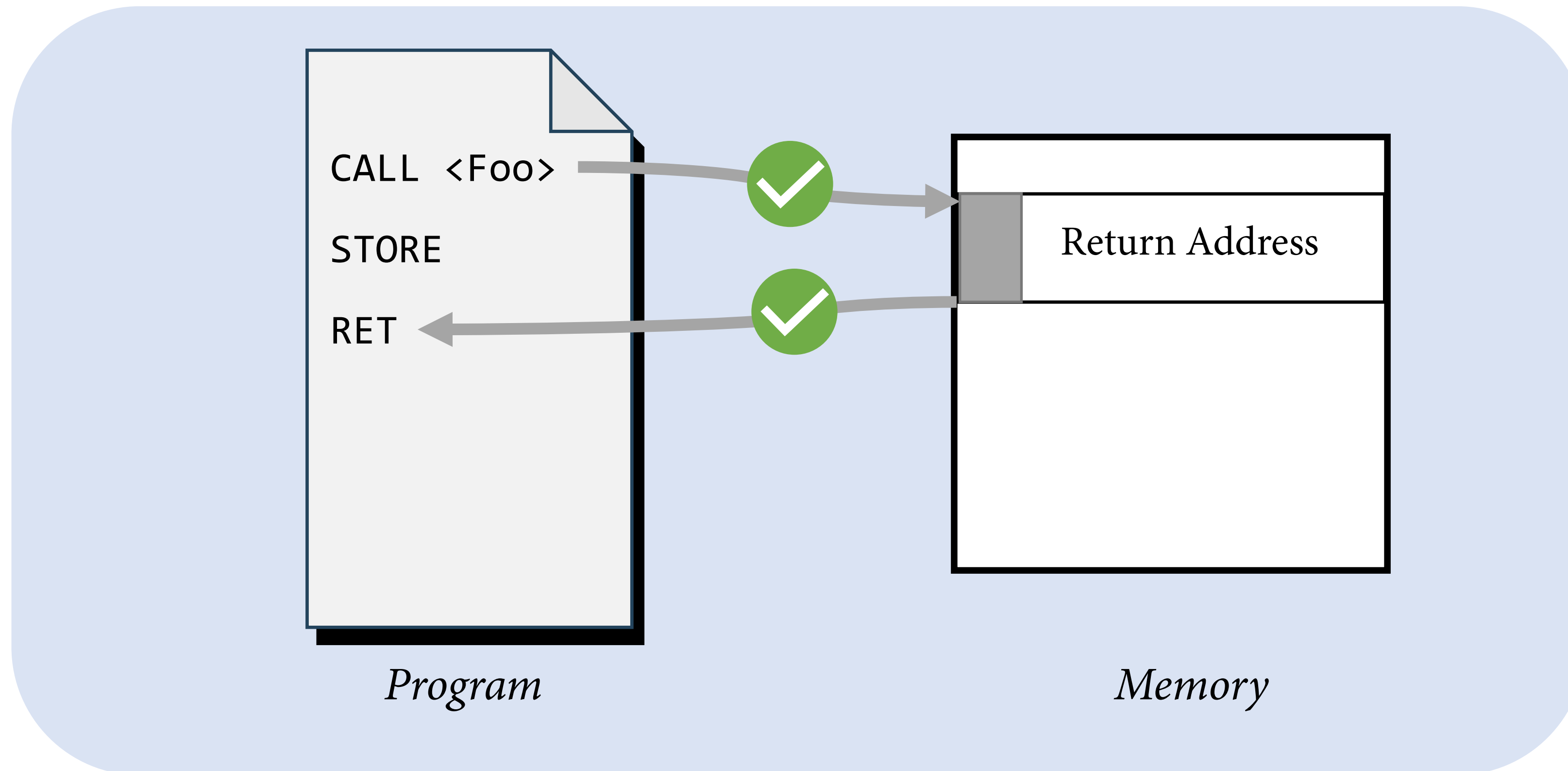

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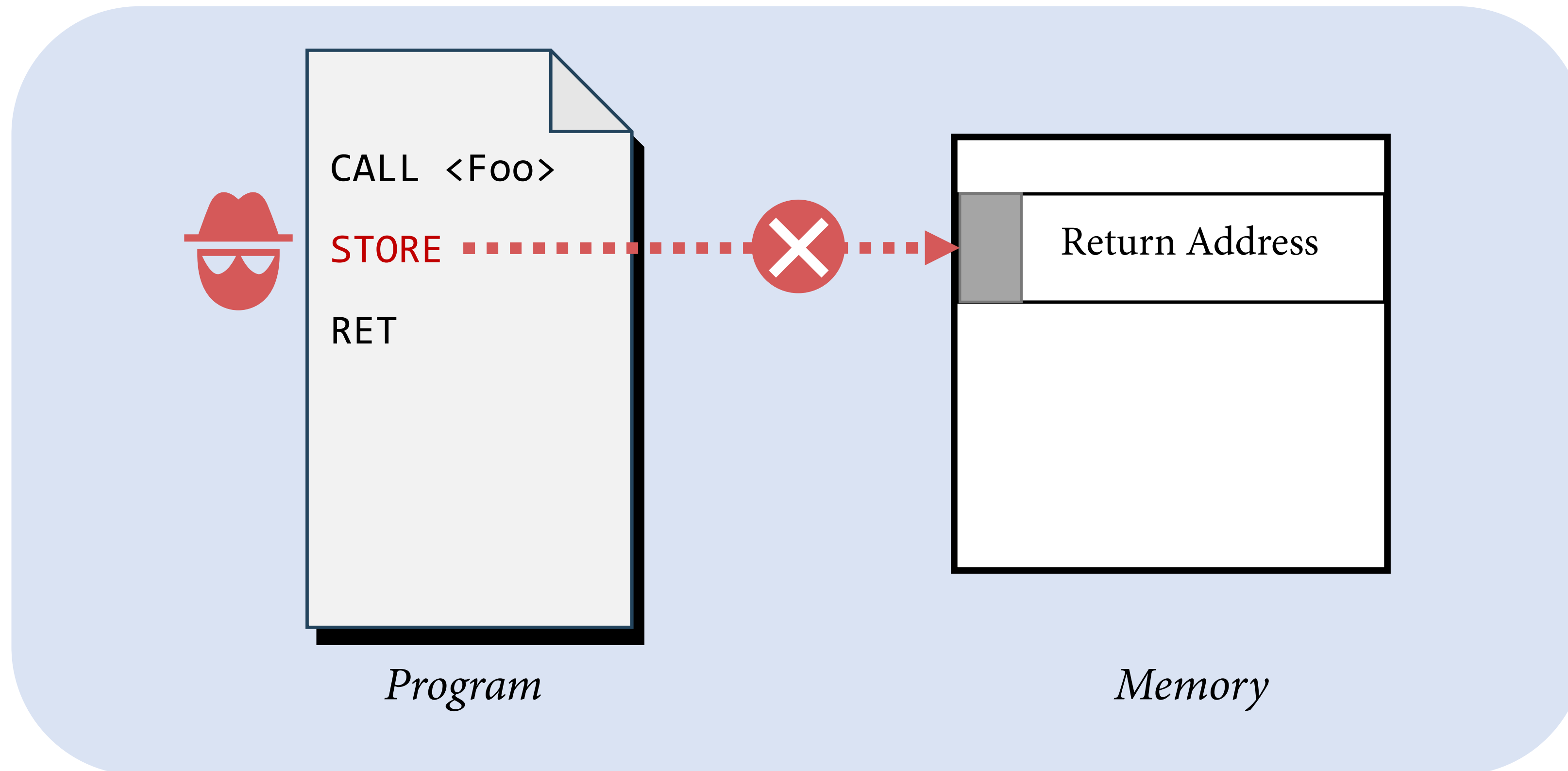

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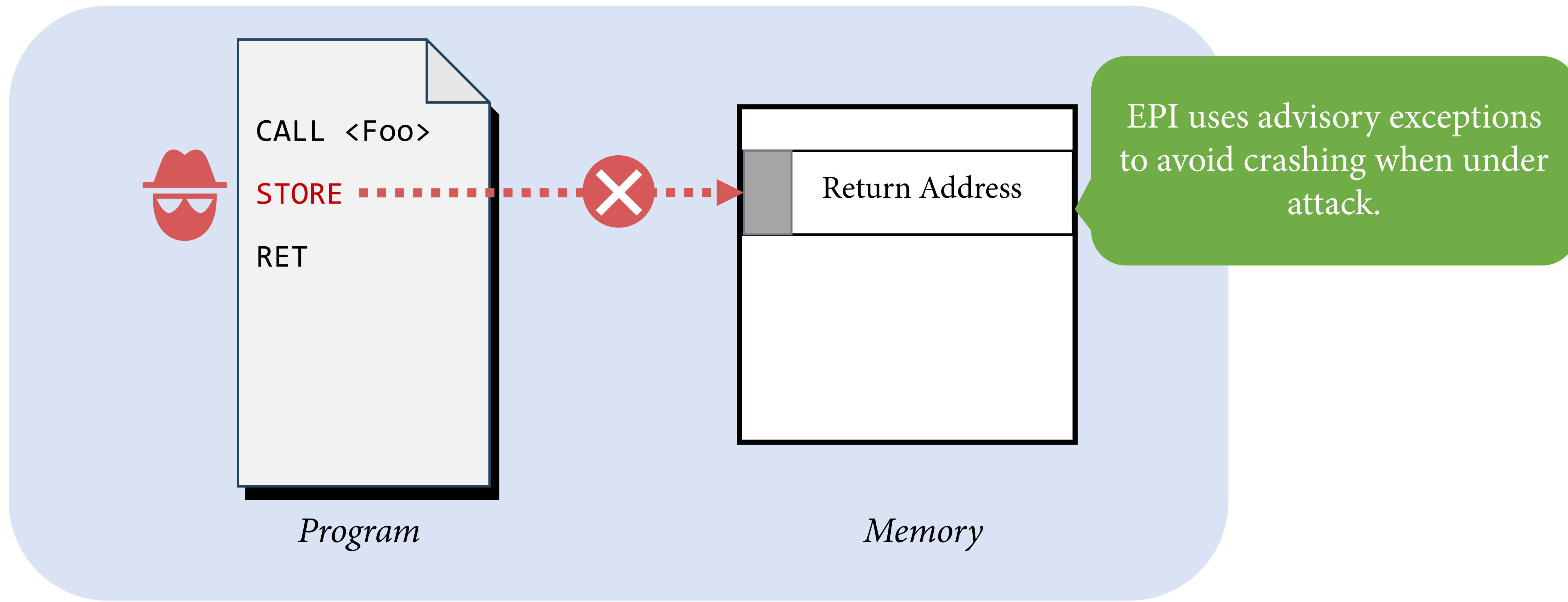


Code Pointer Integrity

CPtrST

...

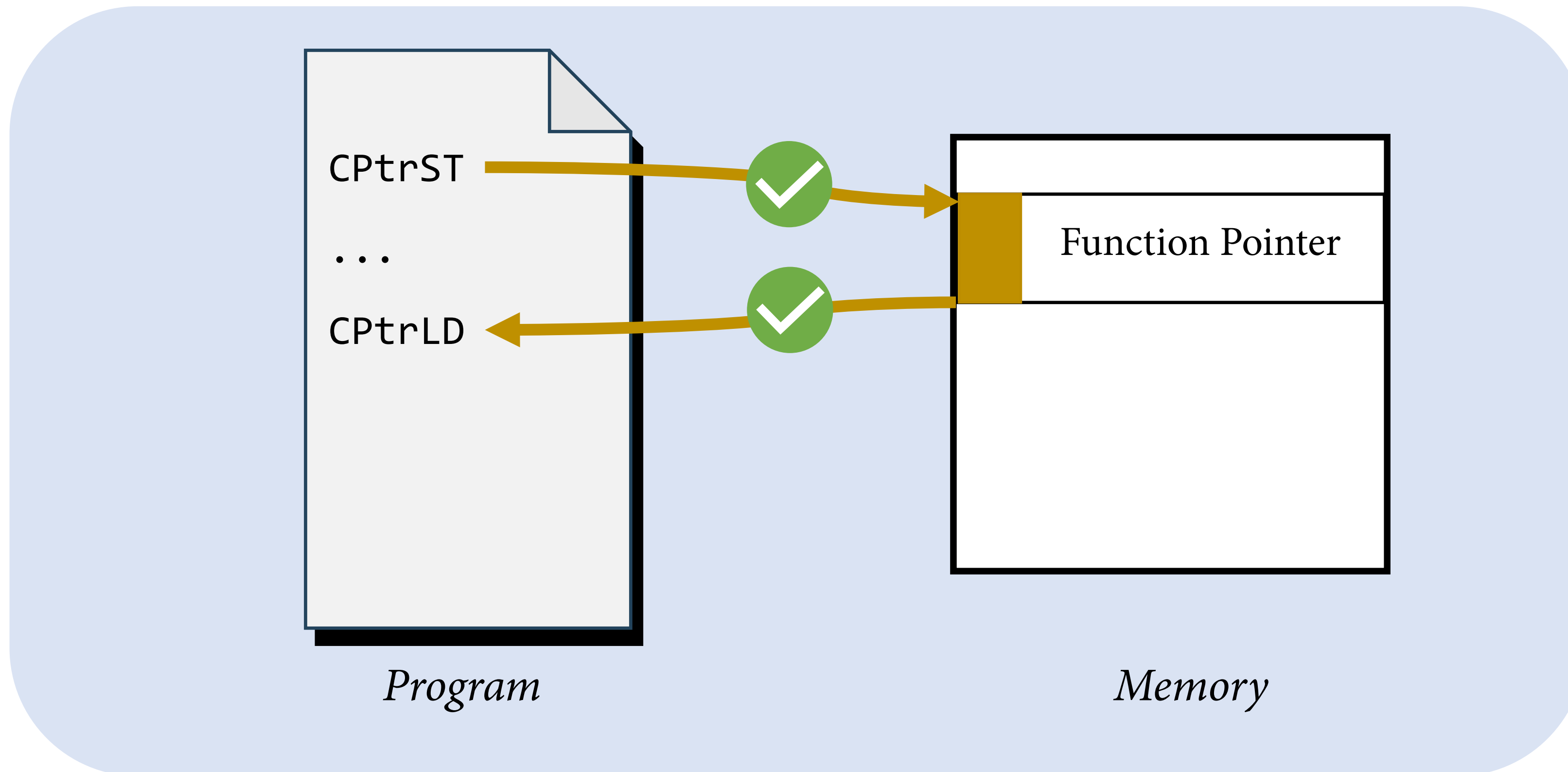
CPtrLD

Function Pointer

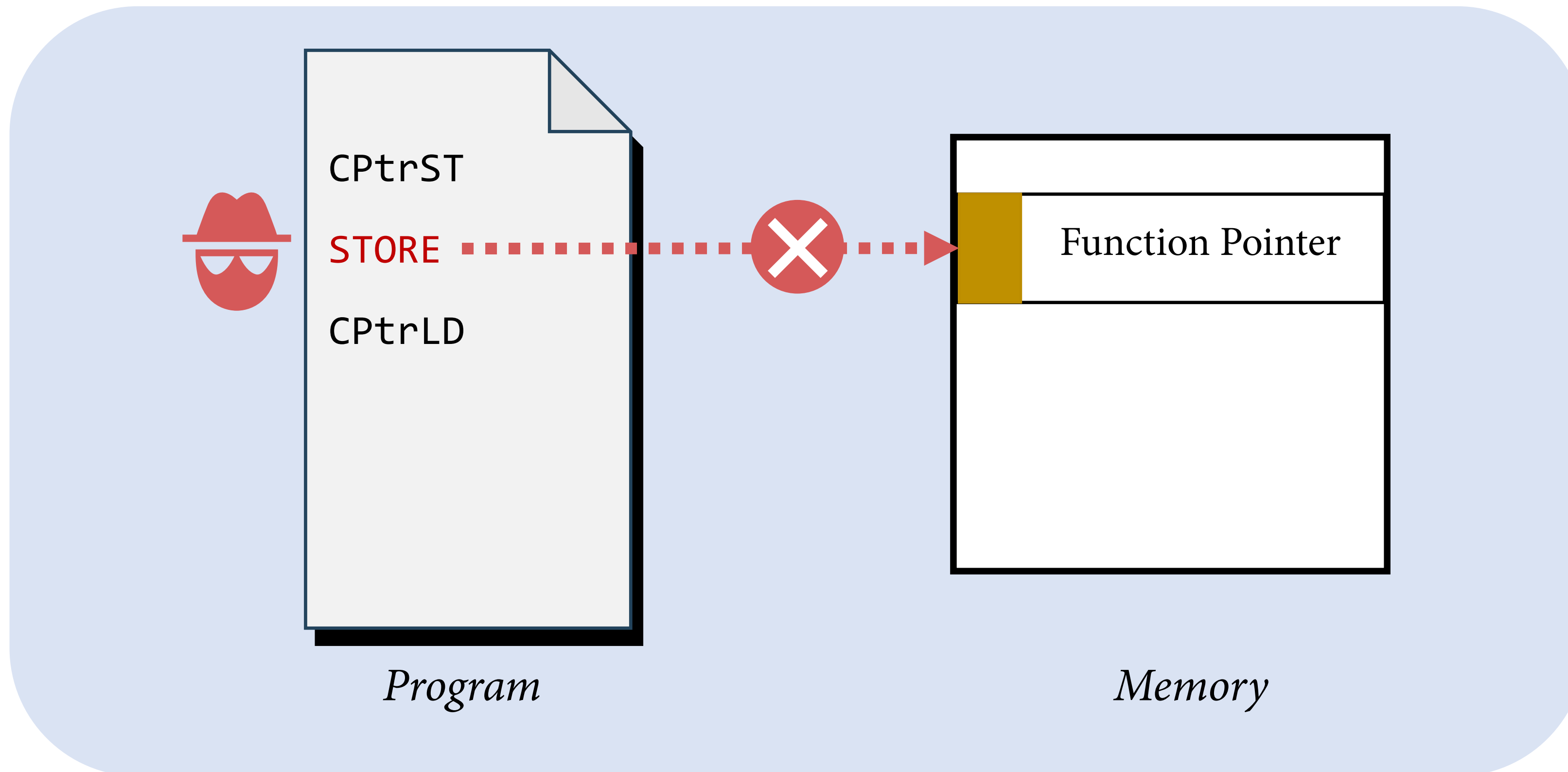
Program

Memory

Code Pointer Integrity

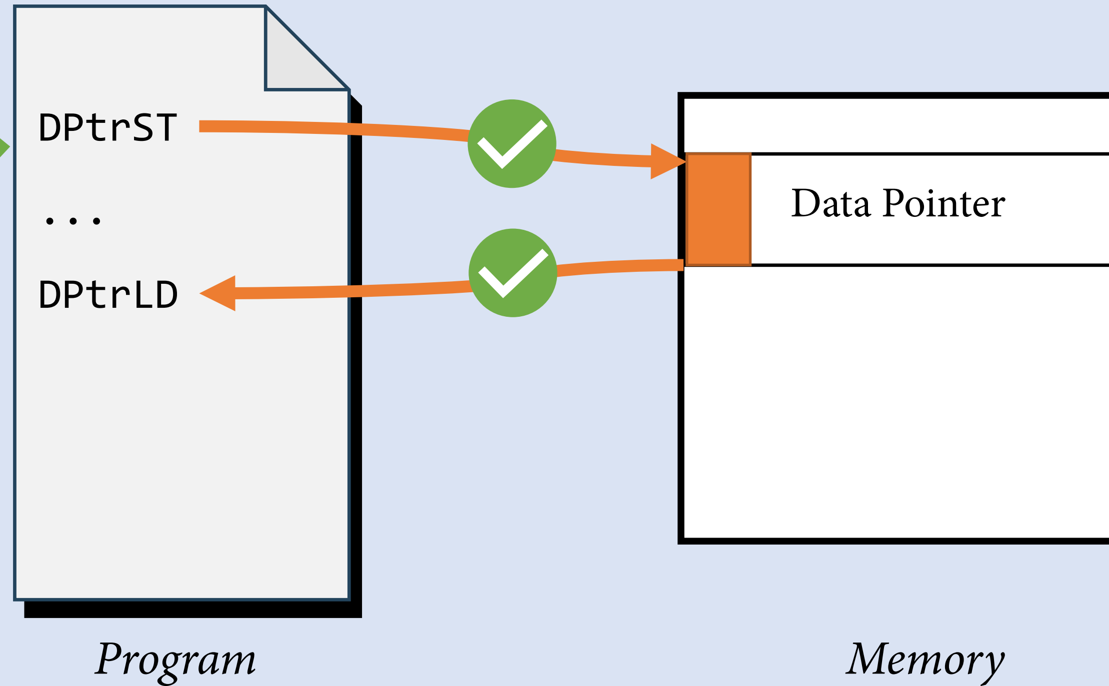


Code Pointer Integrity



Data Pointer Integrity

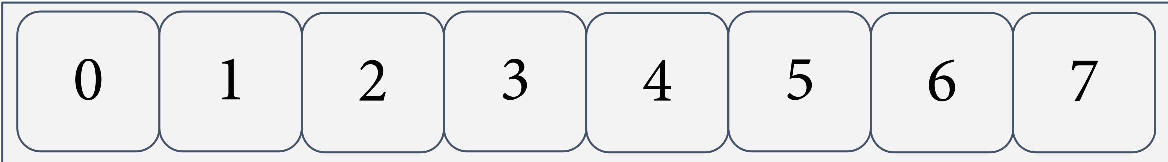
Works in the same way as Code Pointer Integrity but for data pointers!



EPI

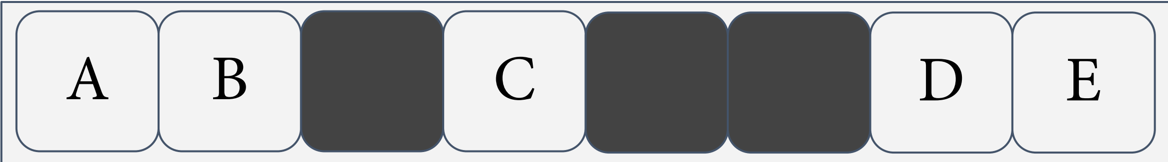
Cache Line Formats

Cache Line Formats



Normal

Cache Line Formats



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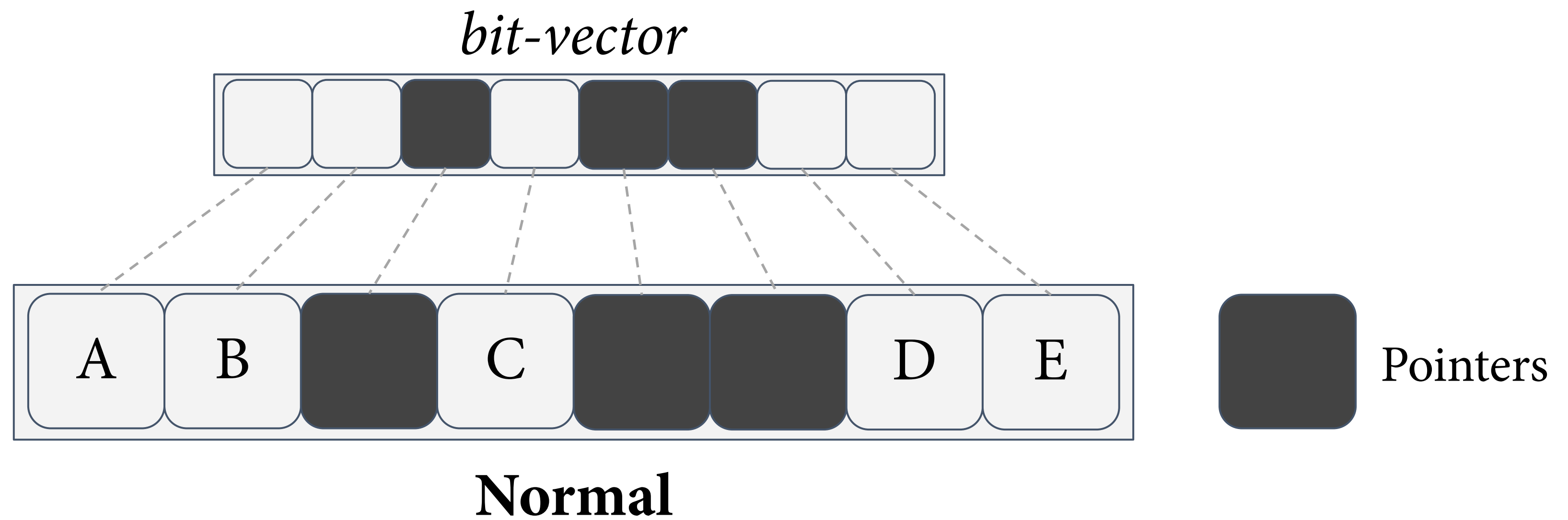
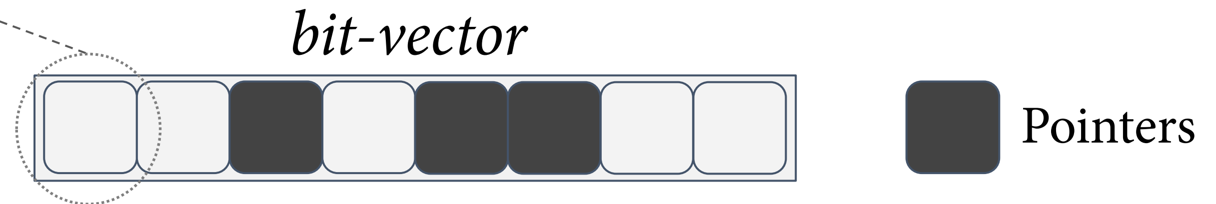


Cache Line Formats

Format Encoding Table

Type	Bits
Return address	01

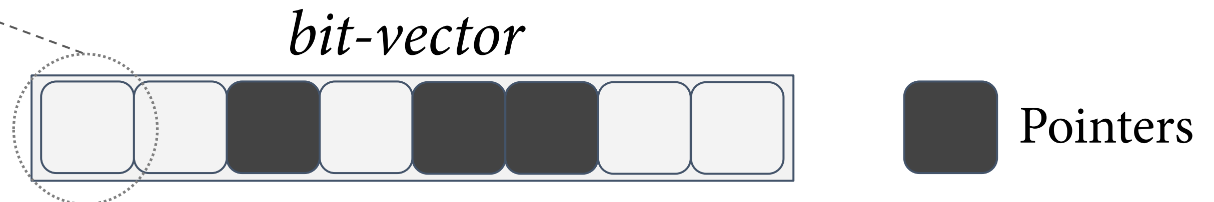


Normal

Cache Line Formats

Format Encoding Table

Type	Bits
Return address	01
Function pointer	10

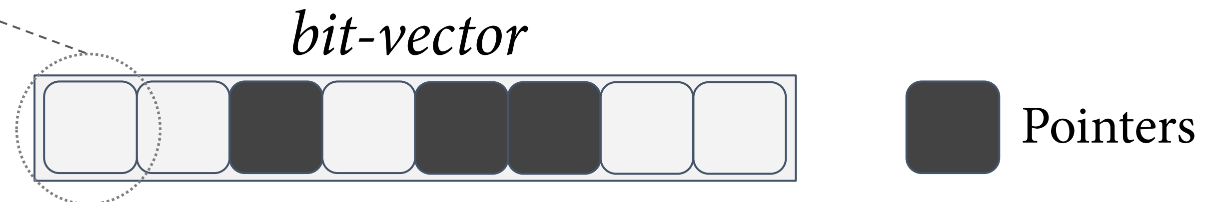


Normal

Cache Line Formats

Format Encoding Table

Type	Bits
Return address	01
Function pointer	10
Data pointer	11

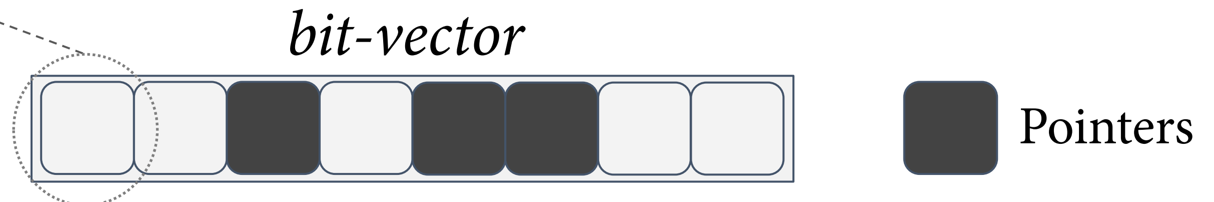


Normal

Cache Line Formats

Format Encoding Table

Type	Bits
Regular data	00
Return address	01
Function pointer	10
Data pointer	11



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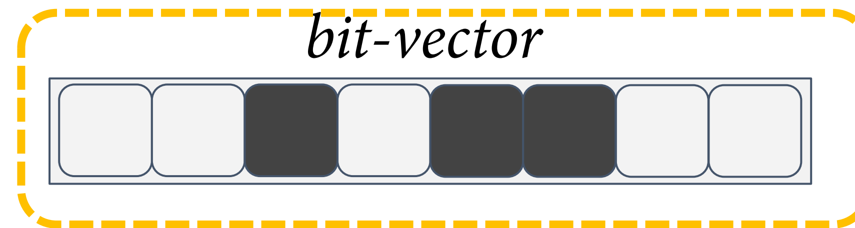
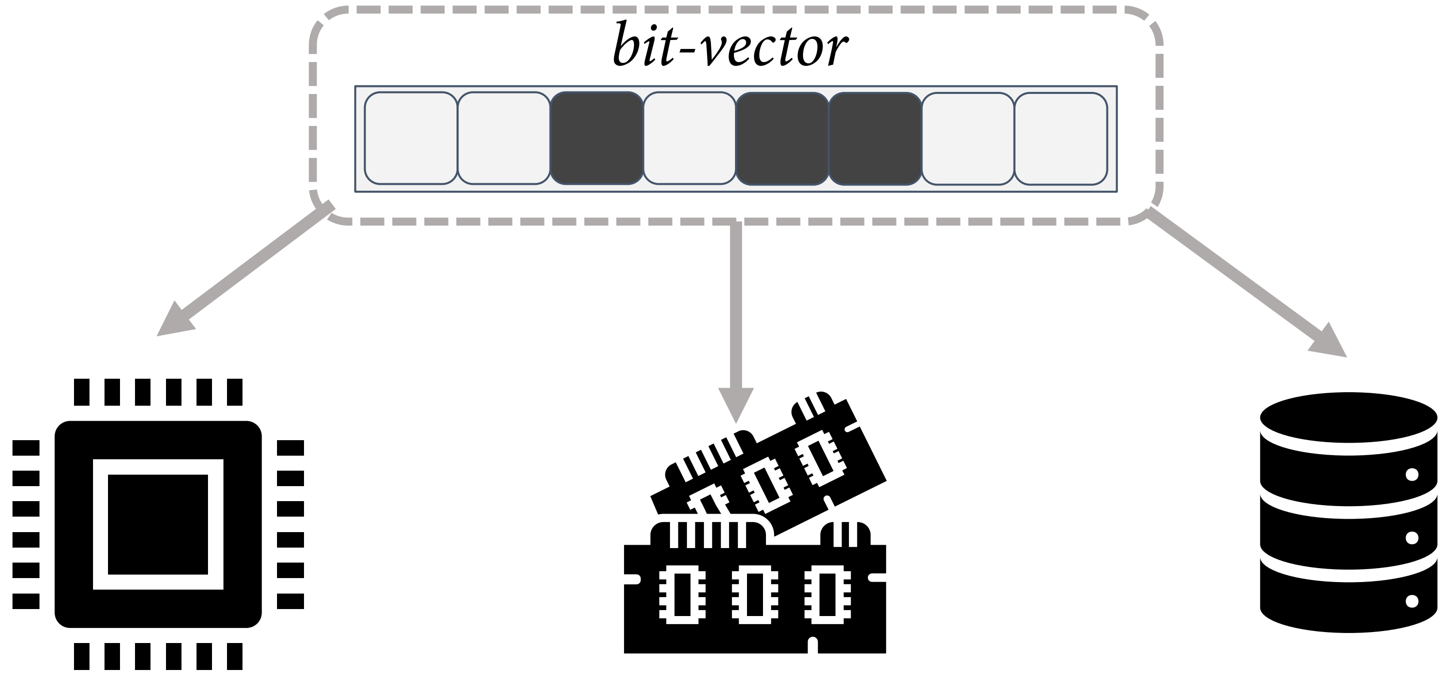


This introduces a 6.25% area overhead.

Normal

Cache Line Formats

Using a bit-vector throughout the memory hierarchy is **inefficient!**



Cache Line Formats

With EPI, we encode metadata **within** unused pointer bits.

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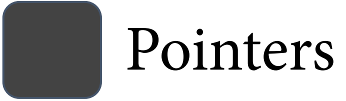

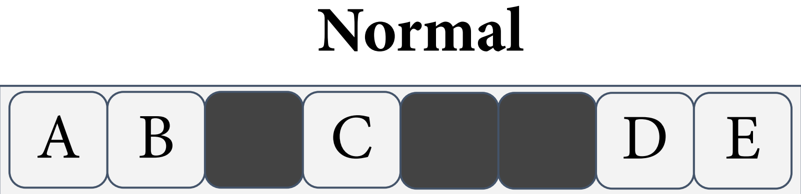

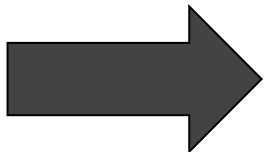

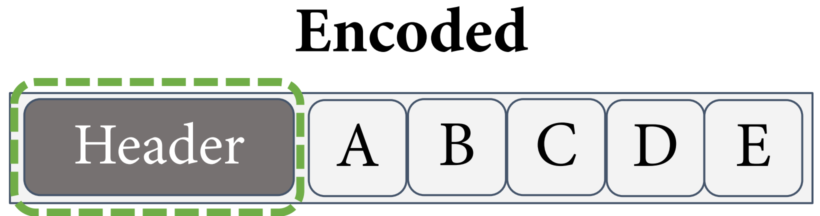

Cache Line Formats

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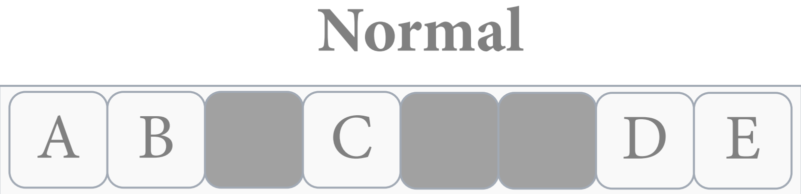

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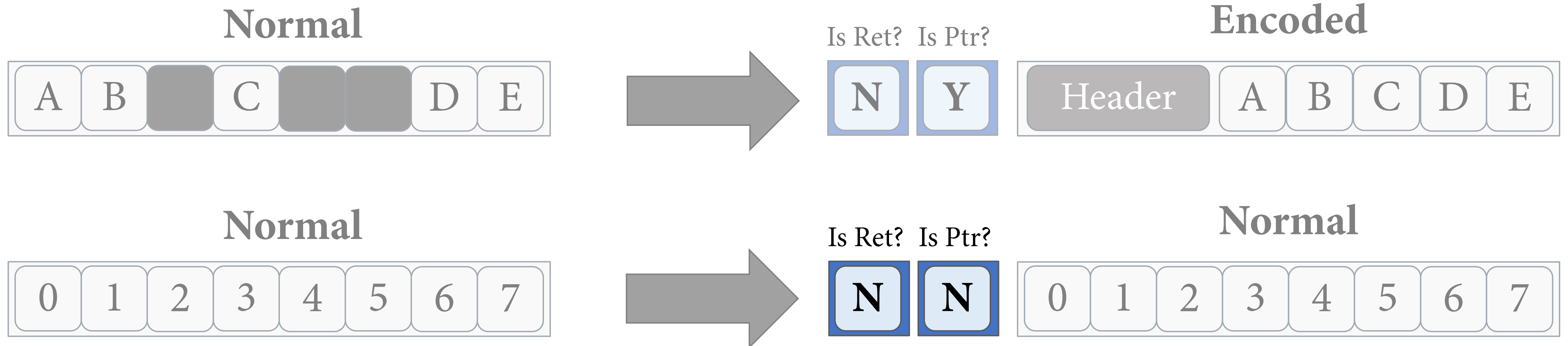
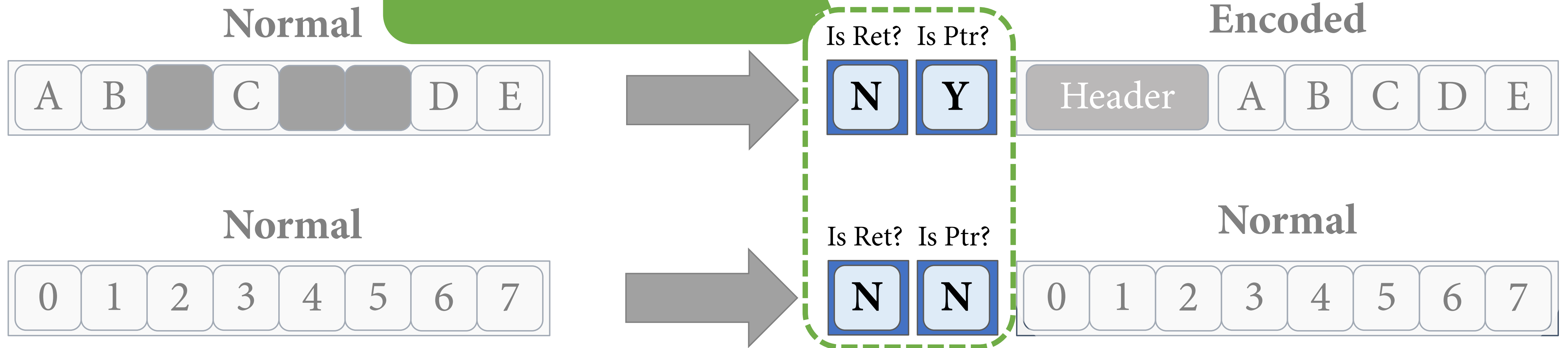


Cache Line Formats

With EPI, we encode metadata **within** unused pointer bits.

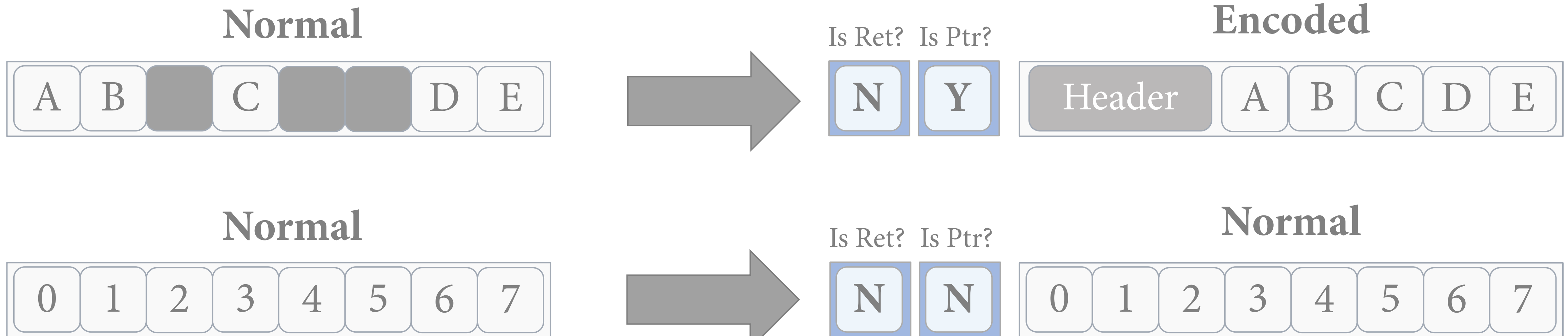
Extra bits add **0.39%** area overhead.

Pointers



Cache Line Formats

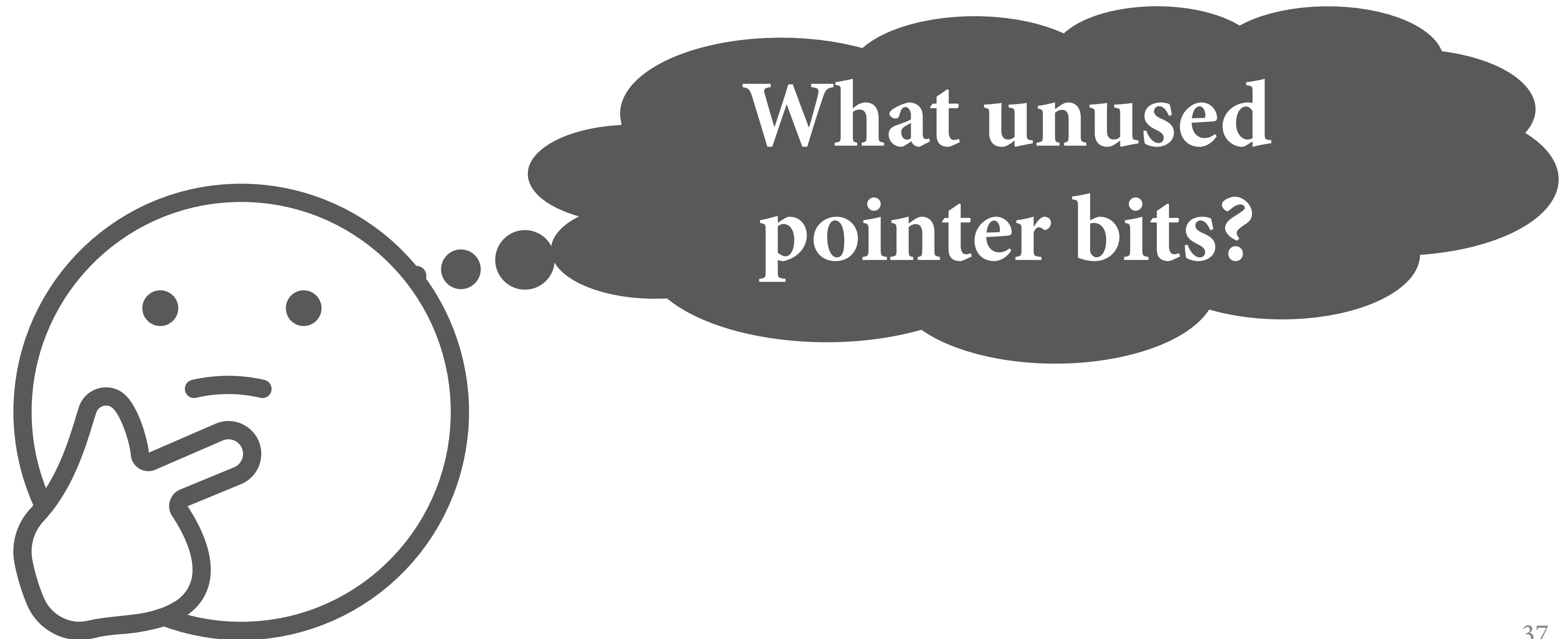
A novel variant of ZeRØ & Califorms



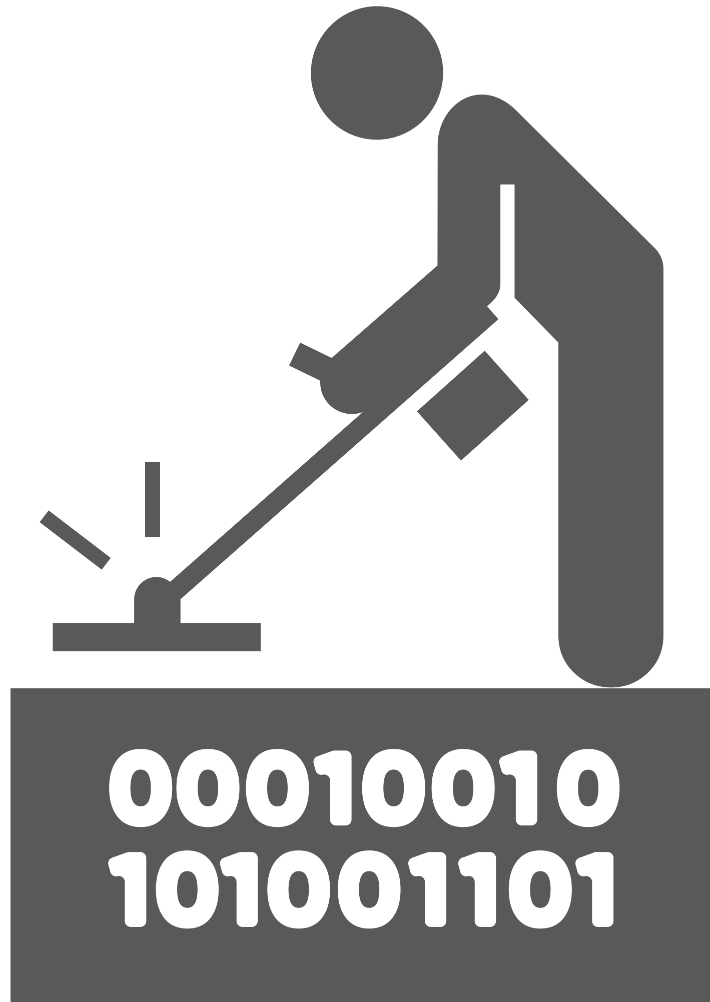
ZeRØ: Zero-Overhead Resilient Operation Under Pointer Integrity Attacks ISCA 2021
Practical Byte-Granular Memory Blacklisting using Califorms MICRO 2019

Cache Line Formats

With EPI, we encode metadata **within** unused pointer bits.



Harvesting Unused Pointer Bits

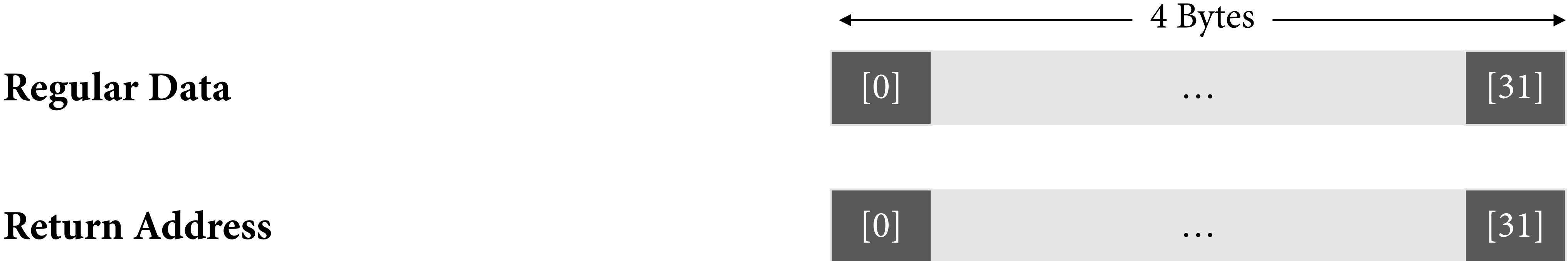


Common software properties allow us harvest extra bits from pointers on 32-bit architectures.

Harvesting Unused Pointer Bits

Regular Data

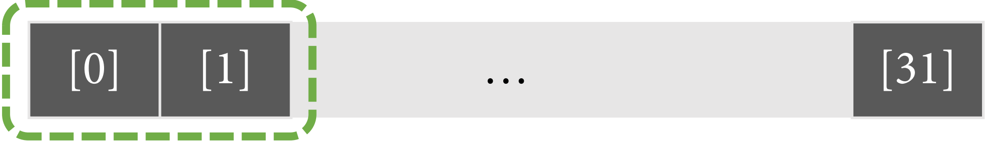
Harvesting Unused Pointer Bits



Harvesting Unused Pointer Bits

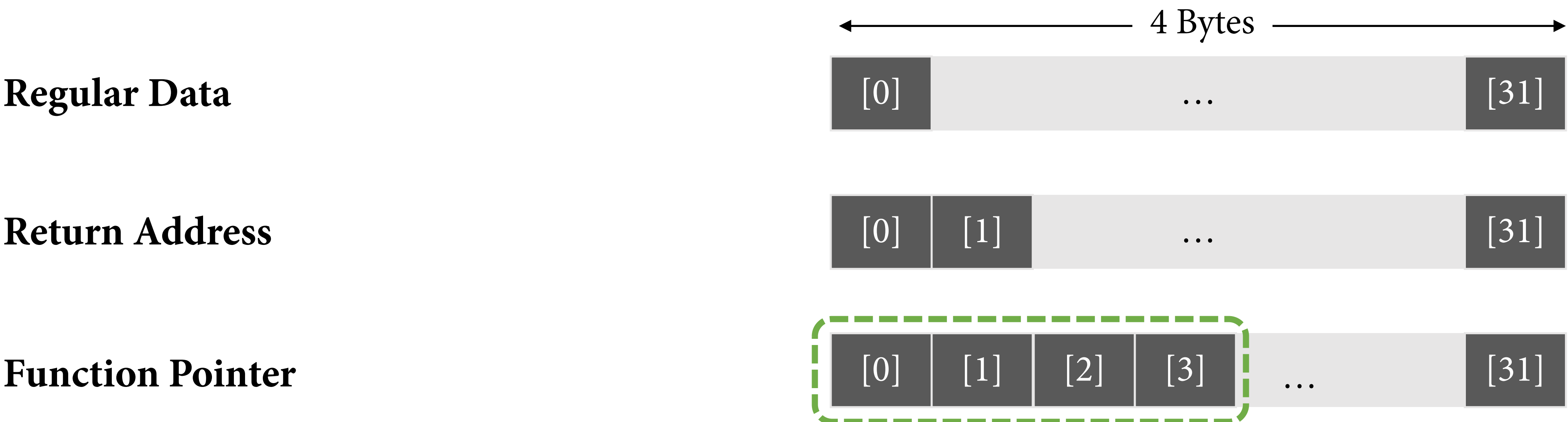
Regular Data

Return Address



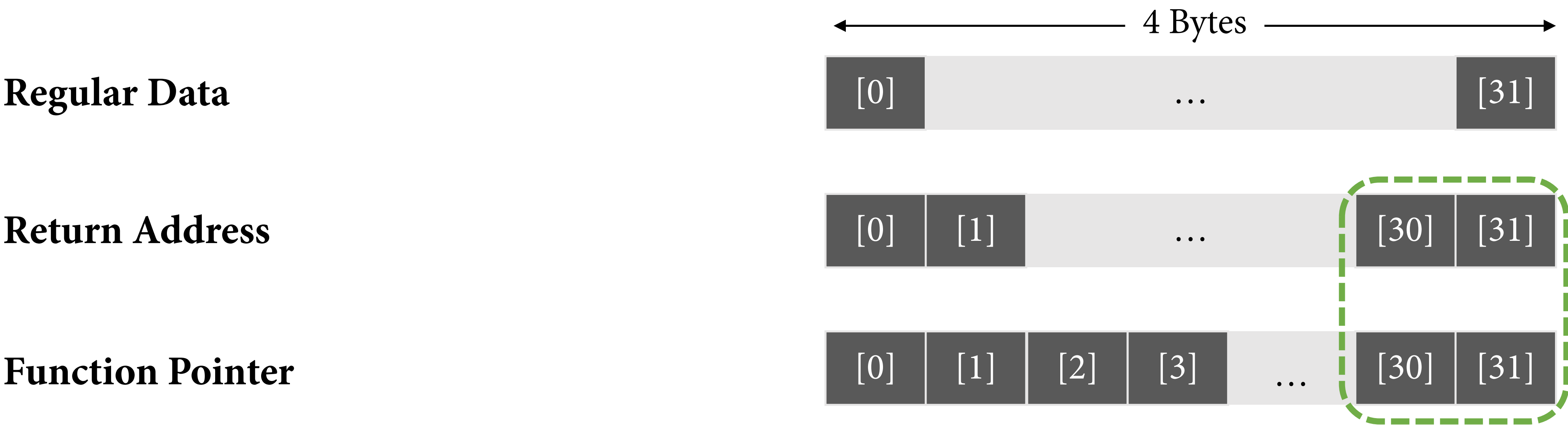
Fixed-width instructions on RISC architectures allow us to harvest the 2 LSBs.

Harvesting Unused Pointer Bits



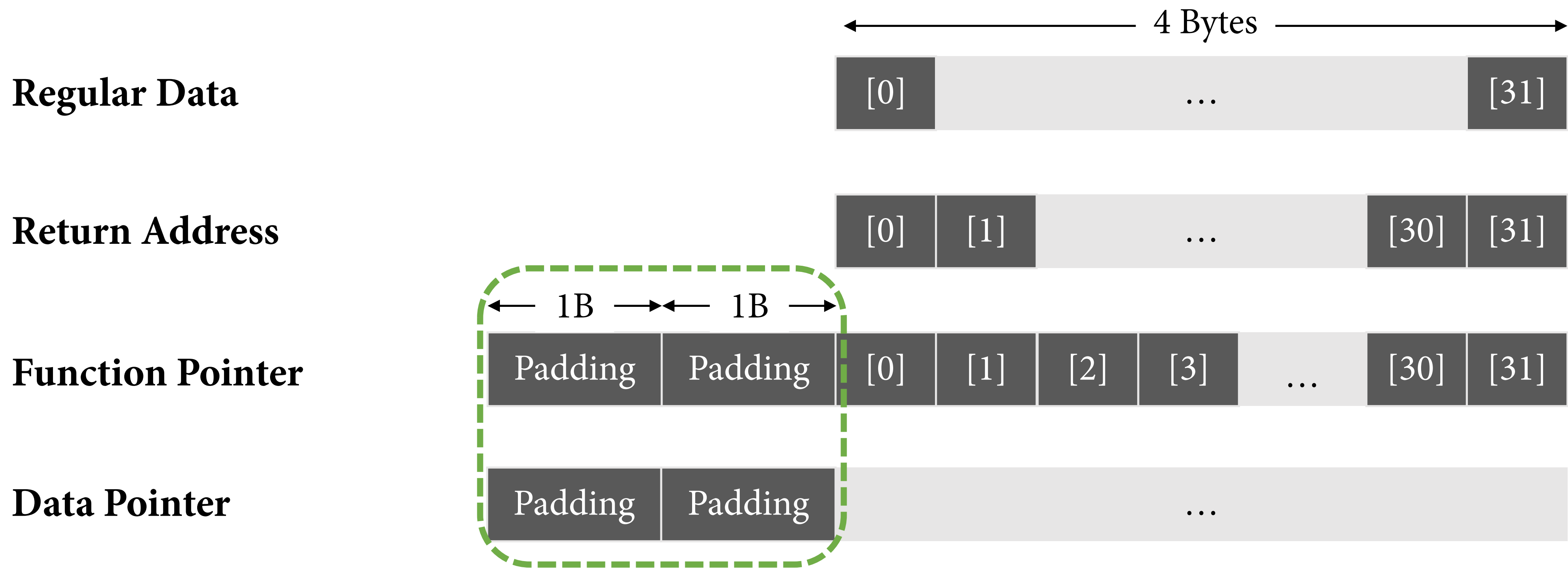
Aligning functions (e.g. `-falign-functions`) allows to harvest the 4 LSBs.

Harvesting Unused Pointer Bits



Compacting the code address space allows us to harvest 2 MSBs.

Harvesting Unused Pointer Bits

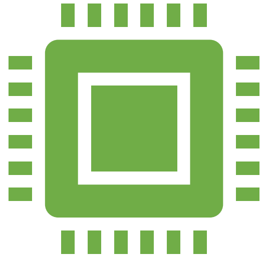


Inserting padding bytes allows us to store a per-pointer ID.

EPI

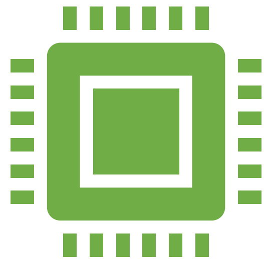
Performance

EPI Performance Overheads



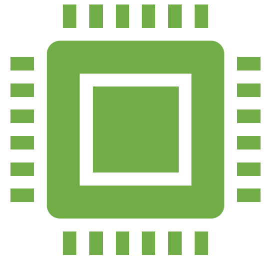
Hardware Modifications

EPI Performance Overheads



Hardware Modifications
Our hardware measurements show minimal latency/area/power overheads.

EPI Performance Overheads



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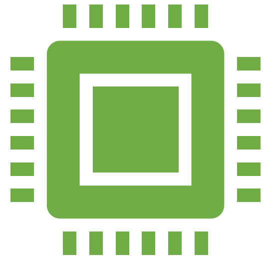
00010010
101001101
00010010
111001001
00010010

Software Modifications

- Our special load/stores do not change the binary size.

EPI Performance Overheads



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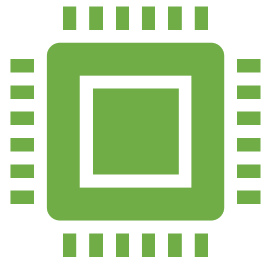

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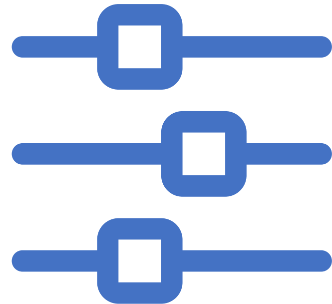
00010010
111001001
00010010

Software Modifications
- Our special load/stores do not change the binary size.
- The `ClearMeta` instructions are only called on memory deallocation.
- Padding bytes are added to pointers only.

Performance Results

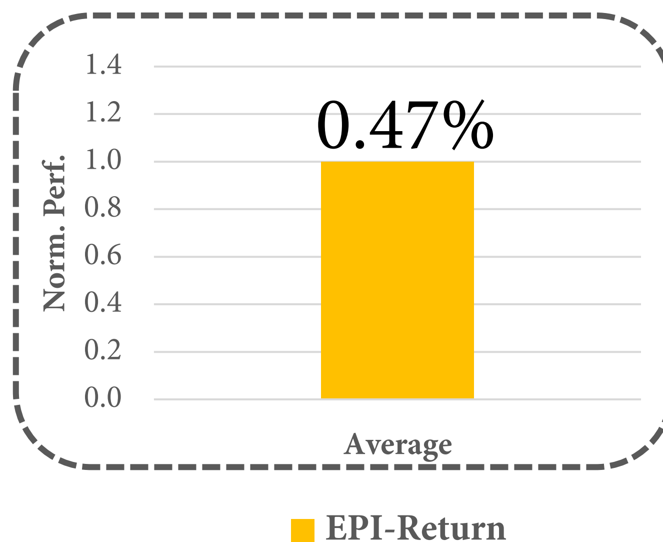


Experimental Setup

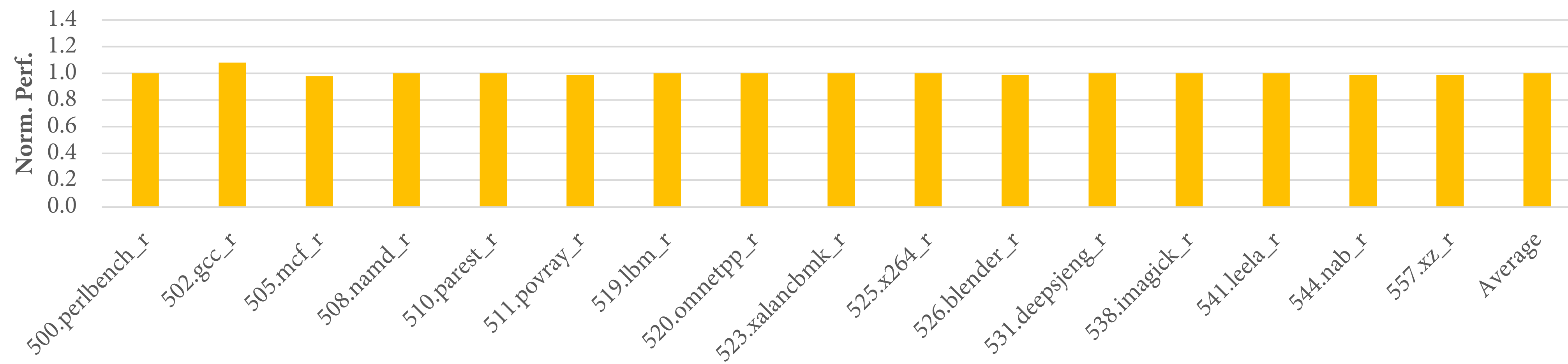
We use emulate EPI on x86_64 by modifying LLVM to emit new instructions.

- `ClearMeta` is emulated using dummy stores.
- Padding bytes & necessary LD/ST emulate extra memory utilization.

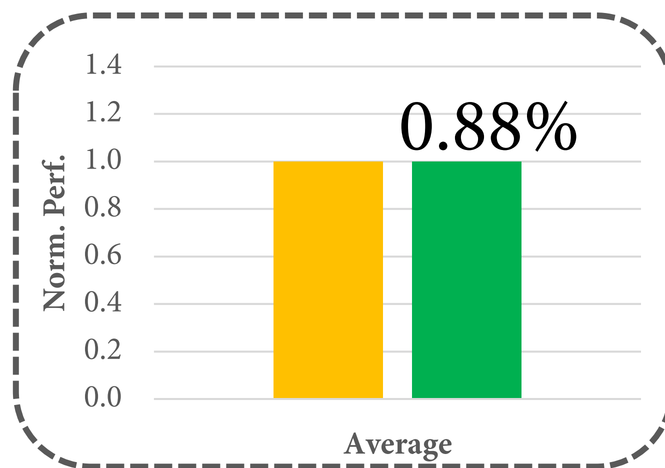
Performance Results



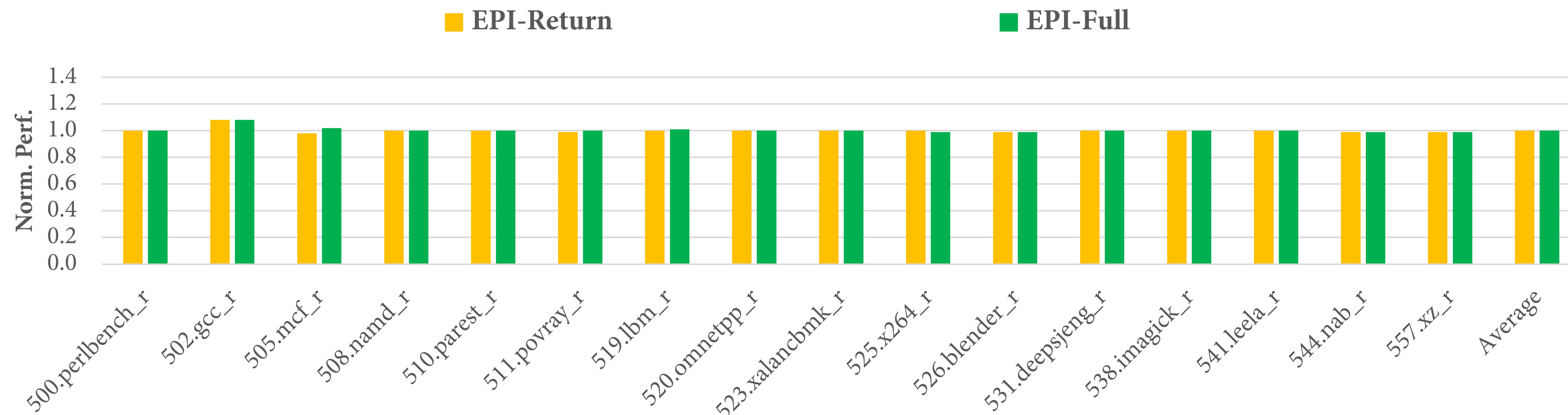
EPI-Return



Performance Results



EPI-Return EPI-Full



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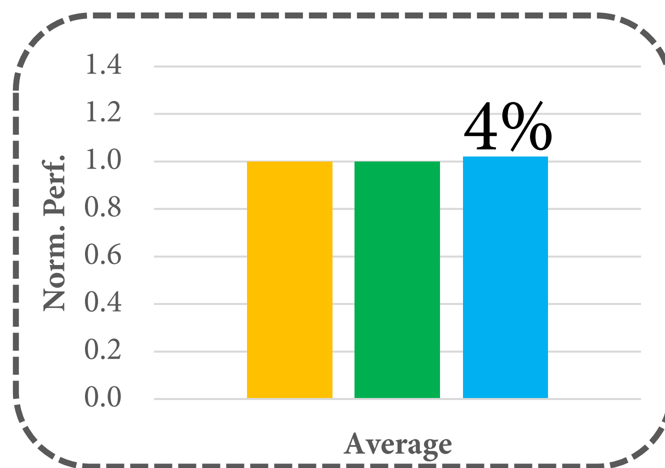

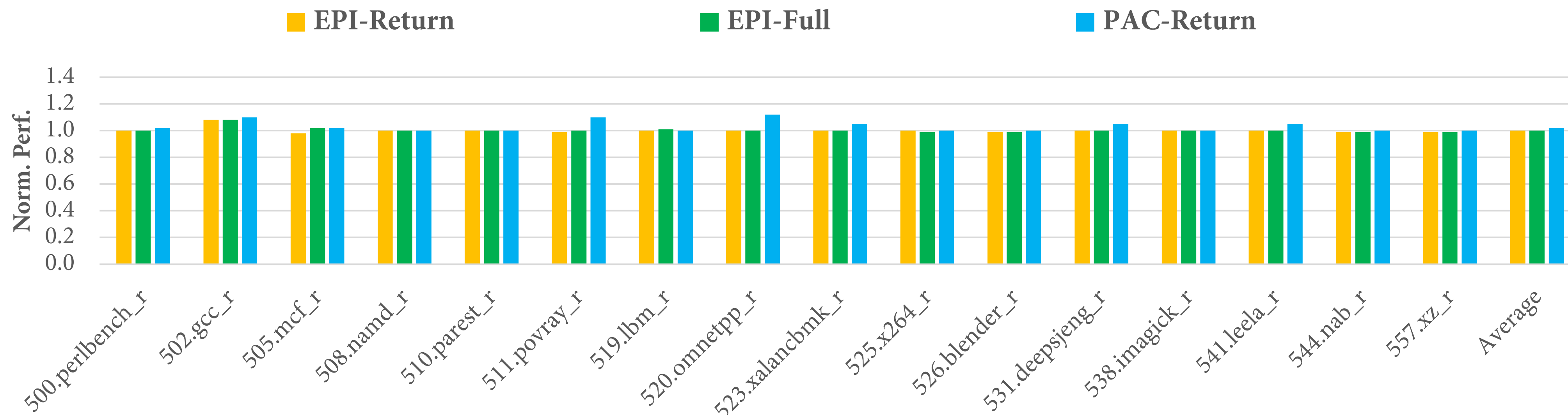

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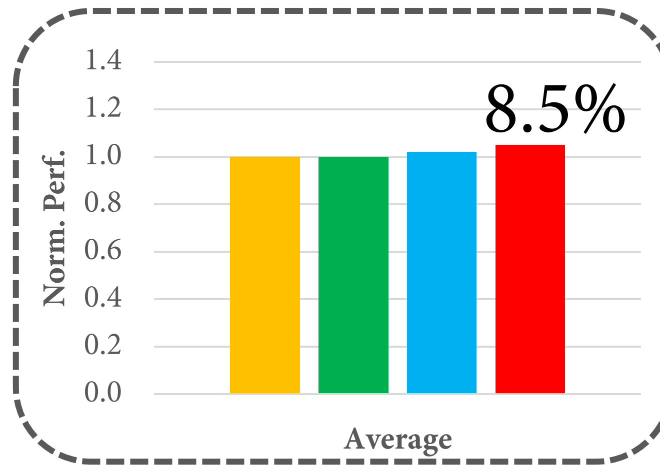

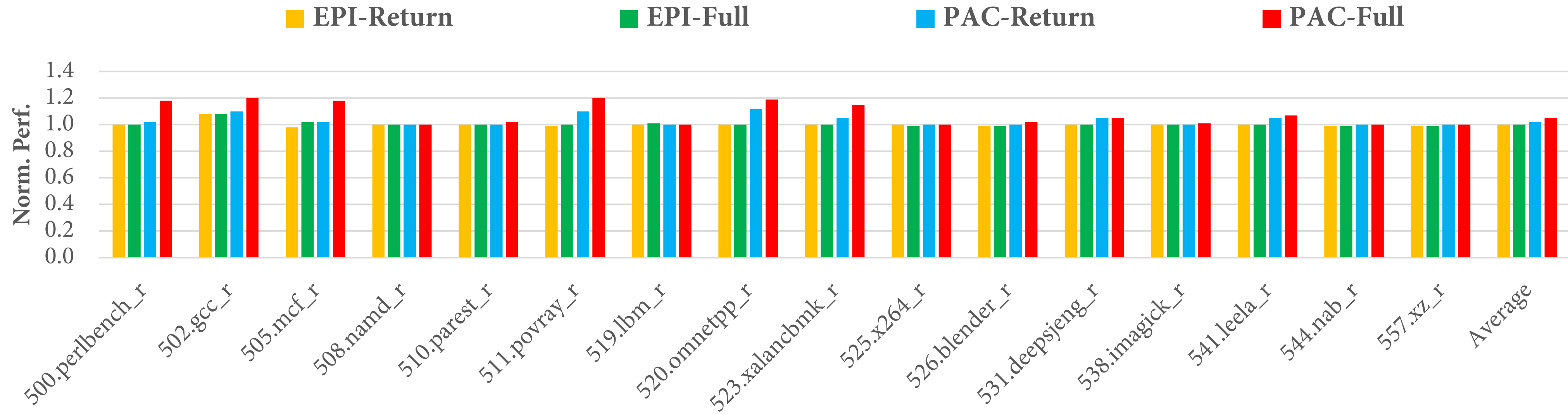

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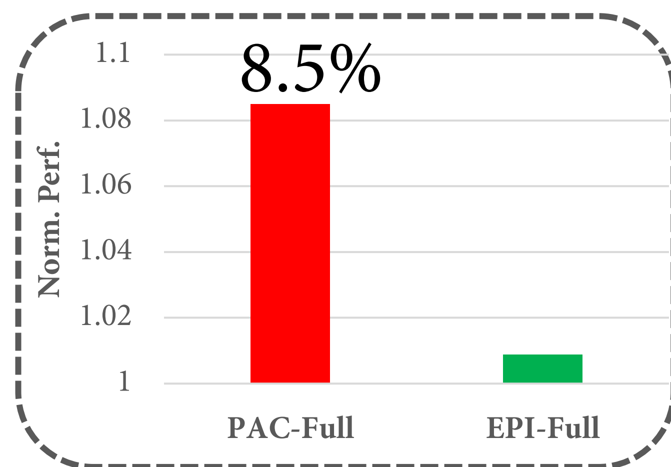
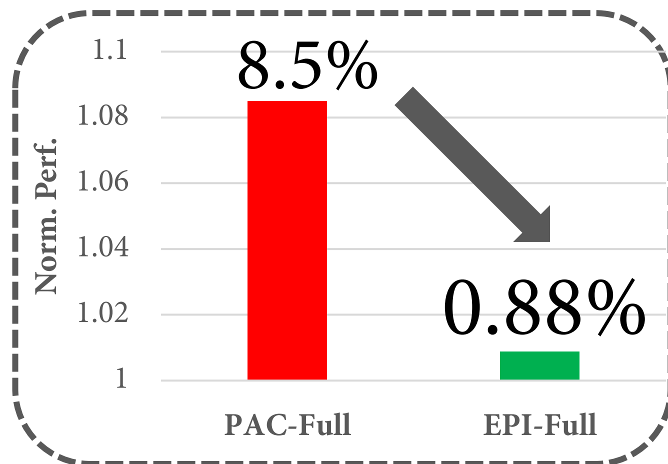


PAC's overheads are attributed to the extra QARMA encryption invocations upon pointer:

- loads/stores
- usages

Performance Results



EPI reduces the average runtime overheads of pointer integrity from 8.5% to 0.88%!

No Pointer Manipulation
Protects against all known pointer manipulation attacks (e.g. ROP, JOP/COP, COOP, DOP).

Handling Security Violations

Advisory Exceptions
- Skip faulty instructions.
- Do NOT crash the running process.

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Permit List
- Initialized during program startup

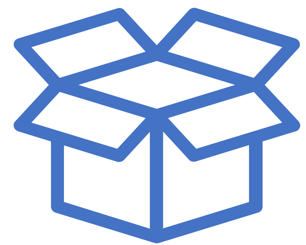
Advisory Exceptions

- Skip faulty instructions.
- Do NOT crash the running process.

Permit List

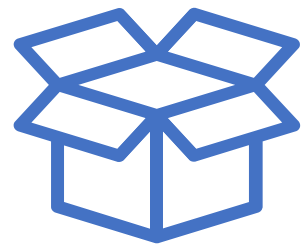
- Initialized during program startup
- Avoid false alarms for non-type aware functions (e.g., `memcpy` and `memmove`)

Handling Third Party Code



We can pick from the following options:

Handling Third Party Code



We can pick from the following options:

1. **Compile with EPI**
   Compile third party code with EPI support.

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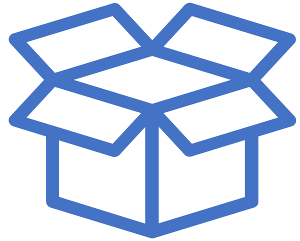
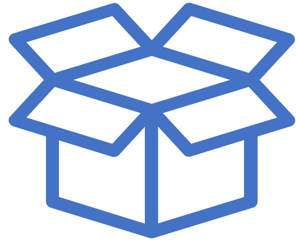


We can pick from the following options:

1. **Compile with EPI**
   Compile third party code with EPI support.

2. **Add to Permit List**
   Add to a permit list during program initialization.

Handling Third Party Code



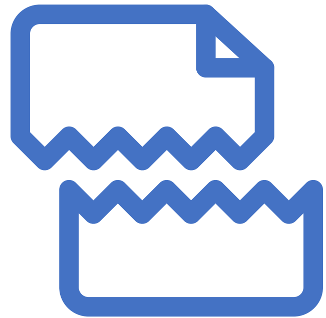
We can pick from the following options:

1. **Compile with EPI**
   Compile third party code with EPI support.

2. **Add to Permit List**
   Add to a permit list during program initialization.

3. **Invoke `ClearMeta`**
   `ClearMeta` is inserted before passing pointers to external libraries.

Limitations



Non-pointer Data Corruption
These attacks require a full memory safety solution.

An efficient pointer integrity mechanism

Specifically tailored for 32-bit embedded systems.

- ✓ **Offers Robust Security**
- ✓ **Easy to Implement**
- ✓ **Minimal Runtime Overheads**
- ✓ **Low Power**
- ✓ **Increased Reliability**