CMPSC 447: Future Directions

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Vulnerability

- Consists of these elements
  - *Flaw*
  - *Accessible to an adversary*
  - *Adversary has ability to exploit*

Can We Really Reduce

- … Vulnerabilities and their exploitation?
- Directions of improvement
  - Reduce/Eliminate Programming Flaws
  - Reduce Accessibility
  - Reduce/Eliminate Exploitability
- Take a look at the prospects of achieving such goals in the future today

Programming w/o Flaws

- Prevent flaws of all kinds
- Memory safety
  - Spatial
  - Type
  - Temporal
- And others
  - Filesystem
  - Information Flow

Memory Safety

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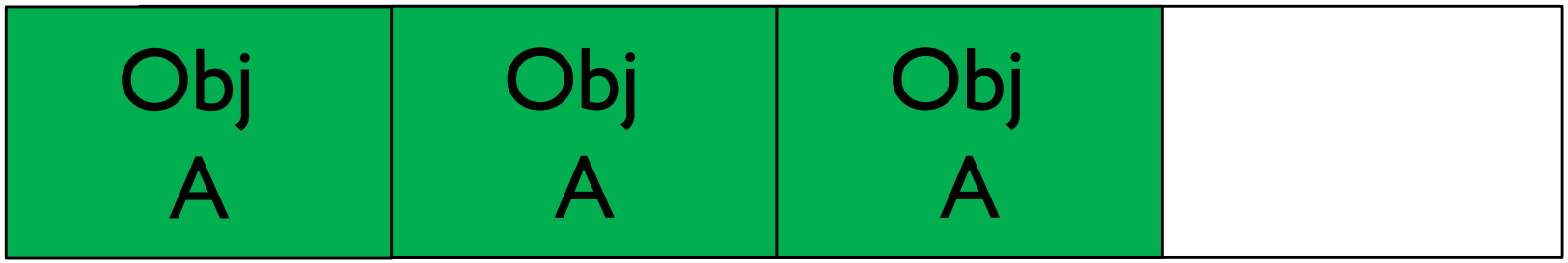
- Prevent safety violations from being possible
  - In most cases, they are not possible
    - Most objects are only referenced by pointers in a safe way
  - In others, we need some checking
    - Hopefully, via safe APIs
  - But, is the checking correct?

Safety Validation

- **For memory safety in C**: CCured system proposed a method identify the pointers only used in memory-safe ways (2002)
  - **Safe**: No pointer arithmetic (spatial) or type casting (type) operations
  - ***Results***: Estimated 90% of pointers are only used in safe operations
  - **Problem**: Does not account for temporal errors
  - Under what conditions are temporal memory safety violations impossible by-design?

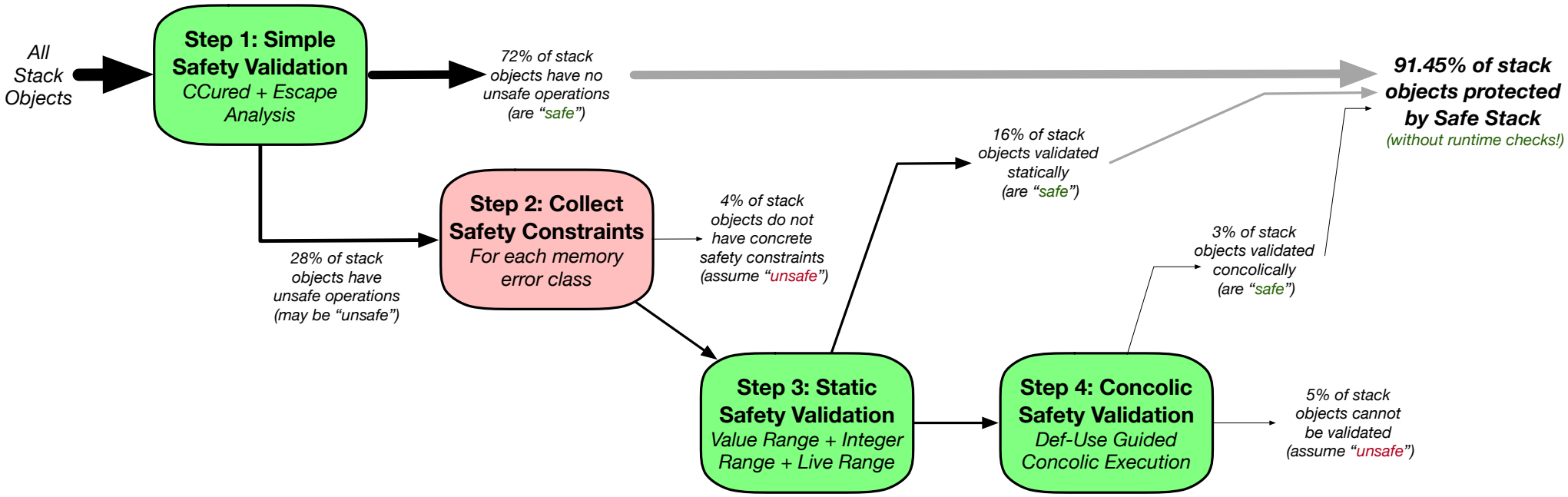
Type-Specific Pools

- Hypothesis: use type-specific allocation
  - All objects and fields are aligned
- Type-specific pools
  - Allocate an object of type A from a memory region containing only objects of type A
  - Keep data and pointers (fields) separate
  - Prevent pointer-region mismatch
- Must all references be of the same type? Default, yes



Possibility of Memory Unsafe

DataGuard System (presented today at NDSS)



Memory Safety

- If a pointer may violate memory safety
  - Need to enforce safety (at runtime)
  - … Correctly

Enforcing Spatial Safety

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- Two ways to enforce spatial safety
  - Check memory bounds
  - Automatic memory resizing
- Checking bounds
  - Make sure that a memory operation is limited to the associated memory region
- Automatic resizing
  - Resize the memory region to accommodate the memory required to satisfy the operation safely
- You now have APIs that check bounds and auto resize

Enforcing Bounds

- Enforce bounds checks
- int *snprintf*(char *S, size_t N, const char *FORMAT, ...);
  - Writes output to buffer S up to N chars (bounds check)
  - Always writes '\0' at end if N>=1 (terminate)
  - Returns "length that would have been written" or negative if error (reports truncation or error)
- Thus, achieves goals of correct bounds checking
  - Enforces bounds, ensures correct C string, and reports truncation or error
    - len = snprintf(buf, buflen, "%s", original_value);
    - if (len < 0 || len >= buflen) … // handle error/truncation
- What is needed for correctness?

Auto Resizing

- What about other functions like scanf?
  - scanf, fscanf, sscanf, vscanf, vsscanf, vfscanf – all unsafe by default
  - Instead, use "%ms" to auto-resize
    - char *buffer = NULL; // Must be set to NULL
    - scanf(buffer, "%ms");
  - Allocates memory for the buffer dynamically to hold input safely – null-terminated, no truncation required
- Note: also, can use for other functions that process input like getline
  - Should check whether the function you use supports this option

Safety from Type Errors

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- Type safety
  - Memory region is only referenced by pointers of one type
  - Corresponding to the type of the memory region allocation
- Memory safety (for regions of multiple types)
  - Memory region may be referenced by pointers of more than one type
  - Semantics of all references correspond to allocation and consistent use of the memory region
  - Think about "question" types in the project

Enforcing Type Safety

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- Type casts create risks of type errors
  - Not type safe
- Any kinds of type casts guaranteed to be memory safe?

Enforcing Type Safety

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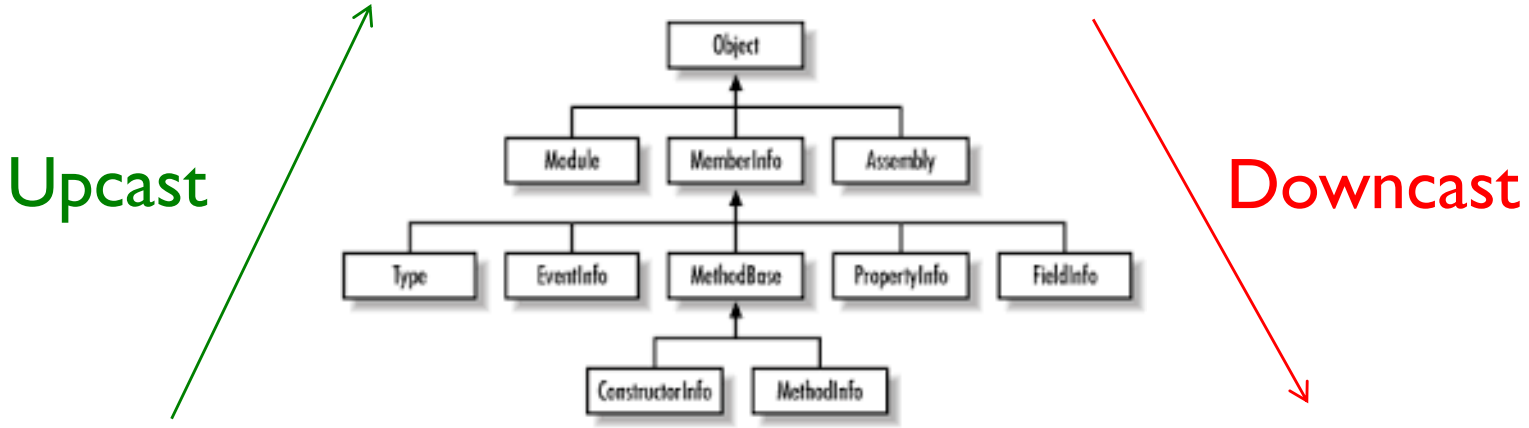
- Type cast risk type errors
  - Not type safe
- Any kinds of type casts guaranteed to be memory safe?
  - Upcasts (spatial and type)
  - Safe integer casts (same value, type) of same size (spatial)
  - Other casts that preserve spatial and type constraints?
- Constraints – do not allow memory errors
  - Ensure separation of data and pointers
  - Ensure an access using a pointer will be within bounds
  - May want more constraints (e.g., value)

Upcasts Are Memory Safe

- Only allow "upcasts" for type casts
  - An "upcast" from a child data type to a parent data type
    - Reduces fields – no overflow possible, fields are same type
  - Turn a downcast into an upcast – how?
    - If you can compute the set of types that may access a memory region



Tagged Casts Can Be Safe

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- A tagged union is a data structure that has multiple, pre-defined types
  - Since we know the pre-defined sets of type for the memory region
  - We can limit the types of pointers that may access the memory region
  - And we can validate ahead-of-time that the combination of types is memory safe
    - E.g., pointer fields are only aligned with pointer fields
- Problem: Need to find set of pre-defined types

Safety from Temporal Errors

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- Type-specific pools
  - Like type safety
    - Memory region is only referenced by pointers of one type
    - Corresponding to the type of the memory region allocation
  - Like "compatible" tagged unions
    - Could exploit type-specific pools for a compatible set of pre-defined types
    - Multiple types that comply with memory safety requirements
- Otherwise
  - Zeroing pointers at initialization and deallocation seems easiest – can add up as overhead

Detecting Vulnerabilities

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- (1) Using safe APIs
- (2) And having program analyses to detect flaws
  - Fuzzing, static analysis, symbolic execution
- What would you need analyses for?

Programming Safely

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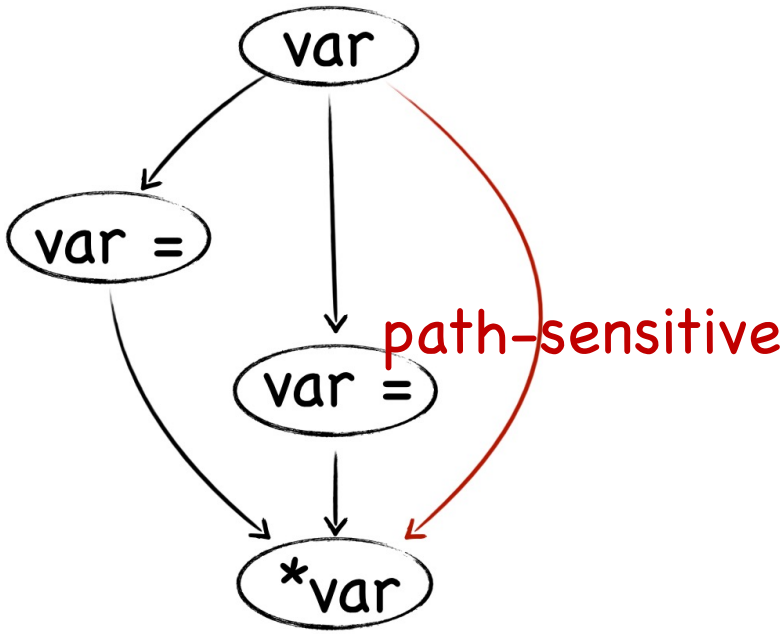
- (1) Using safe APIs
- (2) And having program analyses to detect flaws
  - Fuzzing, static analysis, symbolic execution
- What would you need analyses for?
  - Even use of safe APIs and techniques may be incorrect

Use-Before-Initialization

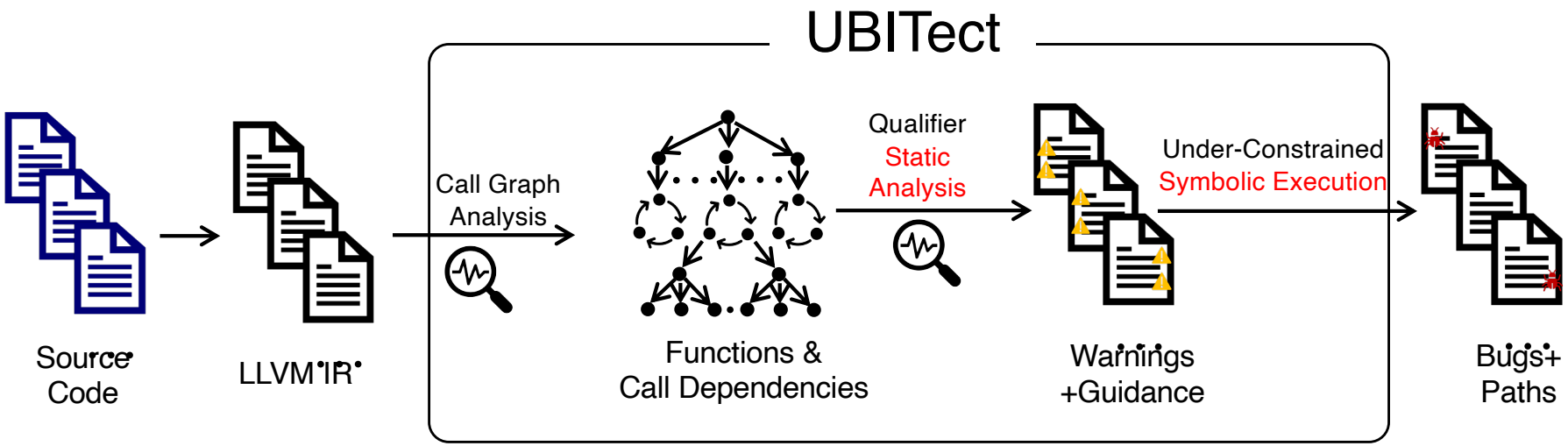
```
1   static int queue_manag(void *data)
2   {
3       /* backlog is declared without initialization */
4       struct crypto_async_request *backlog;
5       if (cpg->eng_st == ENGINE_IDLE) {
6           backlog = crypto_get_backlog(&cpg->queue);
7       }
8       /* Uninitialized backlog is used*/
9       if (backlog) {
10          /* uninitialized pointer dereferenced! */
11          backlog->complete(backlog, -EINPROGRESS);
12      }
13      return 0;
14  }
```

(1) Vulnerable Code



(2) UBI Scenario

Static Analysis for UBI



- Implementation:
  - LLVM 7.0.0
  - 13K+ LoC
  - SE Engine: KLEE

Limiting Access to Flaws

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- If programs may still have flaws, how do we reduce the ability of an adversary to access them?

Limiting Access to Flaws

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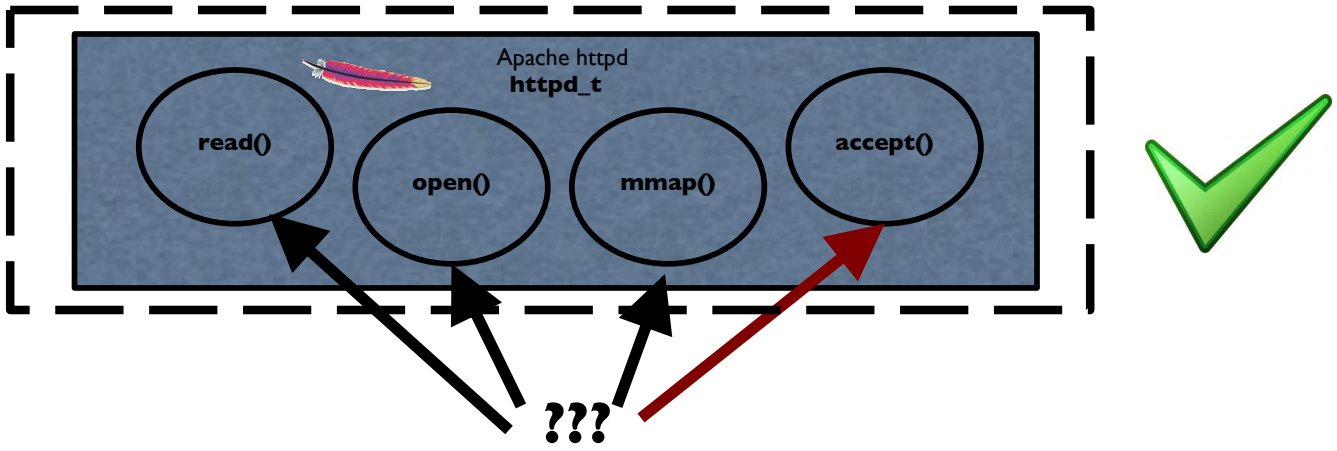
- If programs may still have flaws, how do we reduce the ability of an adversary to access them?
  - Attack surface
    - Limit the places where adversary input is allowed

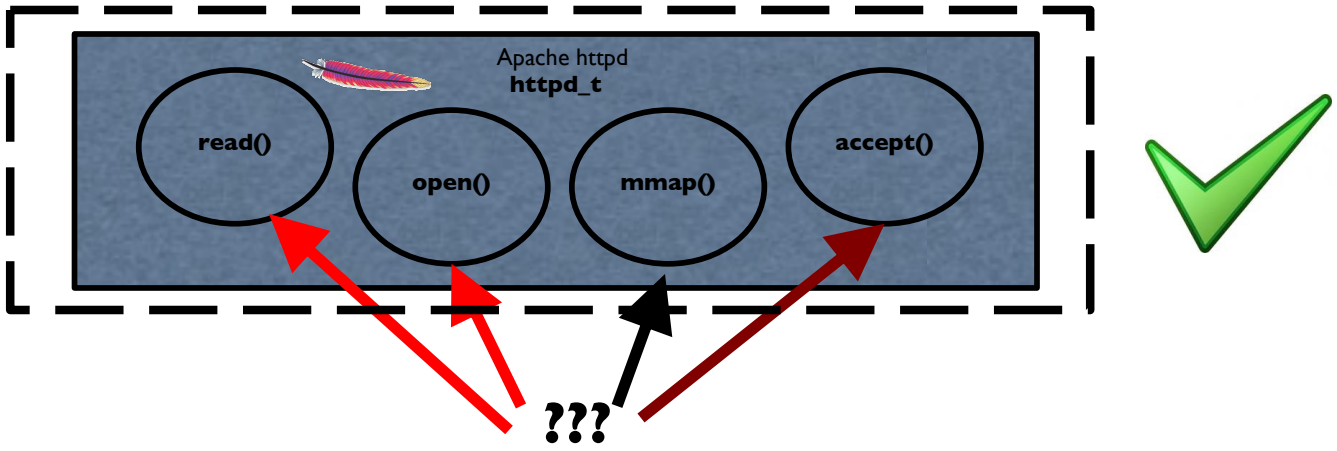
Attack Surface

- Insight: Only a small fraction system calls expect to use adversary-controlled input



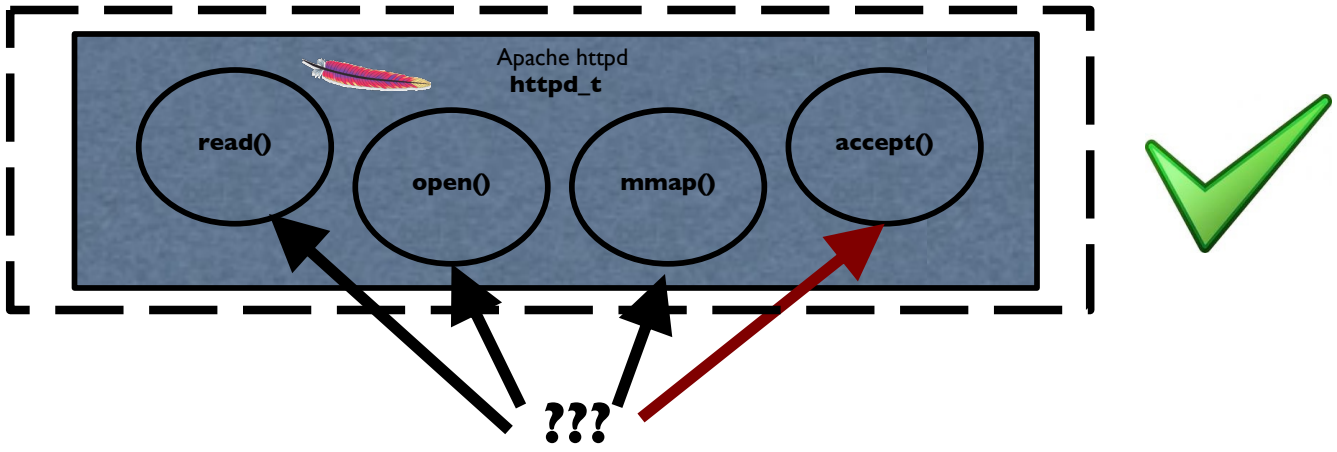
Attack Surface

- Insight: Only a small fraction system calls expect to use adversary-controlled input
  - Any new attack surface is often the source of vulnerabilities



Attack Surface

- Insight: Only a small fraction of program system calls expect to use adversary-controlled input
- Limit the system call to only access "safe" objects



- What is "safe"?

Attack Surface

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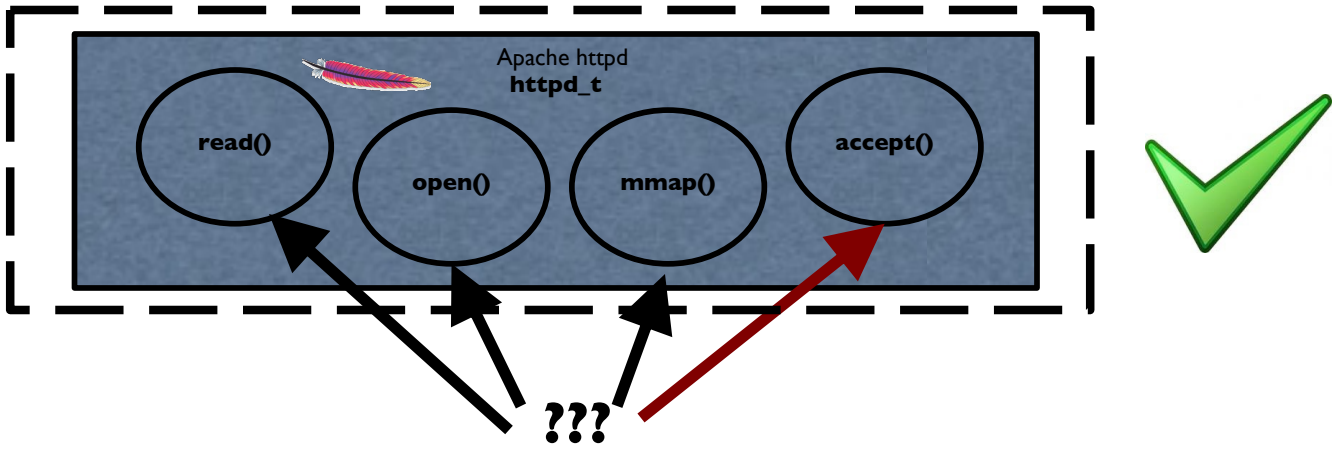

- What is "safe"? Not modifiable by an adversary

Limiting Exploitability of Flaws

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- If programs may still have flaws that adversaries can access, how do we reduce the ability of an adversary to exploit them?
  - Isolation
    - Isolate good data from bad
  - Restriction
    - Limit targets to which a compromised pointer can reference

Isolation

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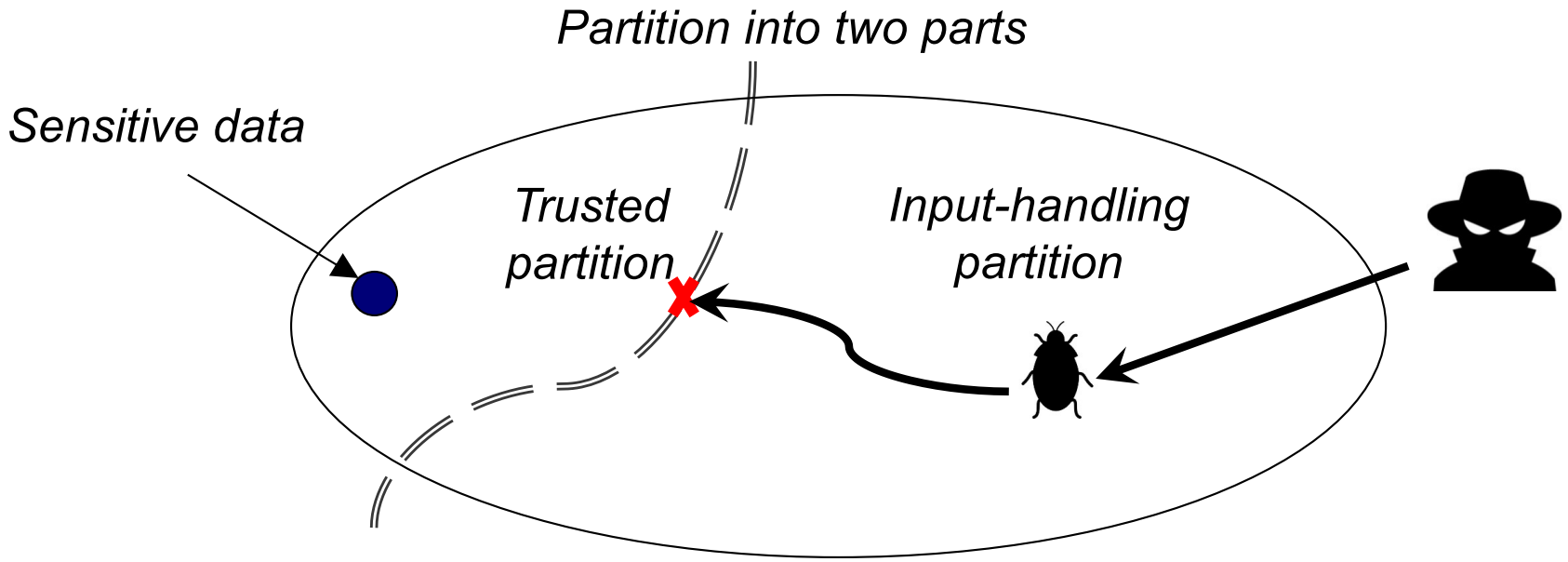
- Isolate data that is safe from memory errors from other unsafe data
  - Only safe memory references possible for all safe objects
- Unsafe memory references are possible via unsafe pointers
  - But, if safe objects are not accessible from those unsafe memory references then they are protected

Motivation for Partitioning

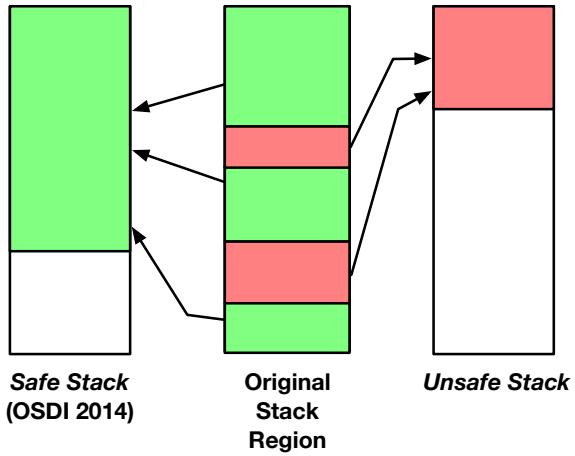
- Split the application into multiple partitions
- Each partition is isolated using some isolation mechanism such as OS processes



Although some partition of a program has been hijacked, sensitive data can still be protected

Multi-Stack (Safe Stack)

- **A separate stack region** for objects validated to be safe from spatial errors (Safe Stack)
- **Results:** Safe stack objects are protected from spatial errors without runtime checks
- **With DataGuard** all objects on the safe stack have been proven safe from all three classes of memory errors
- **Can do same kind of thing with heap objects as well!**
- **But, isolation between stacks is currently implemented by ASLR**



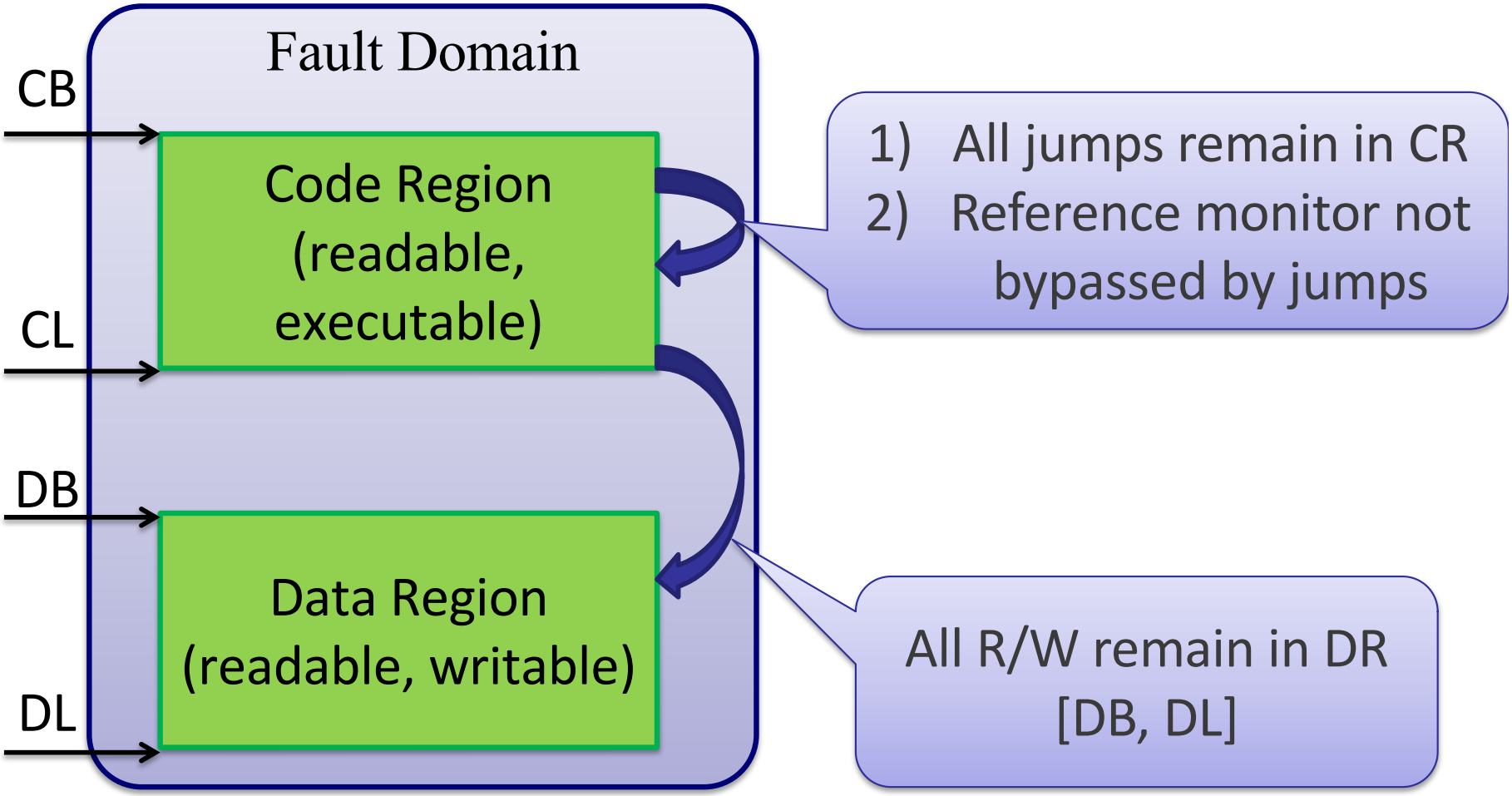
Restriction

- Limit memory accesses only to legal values
  - Any example of this approach you can recall?

Restriction

- Limit memory accesses only to legal values
  - Any example of this approach you can recall?
  - CFI – restrict targets of an indirect call to the CFG
  - SFI – restrict targets of a memory access to a region
  - Privilege separation restricts accesses to the memory regions associated with a subset of functions (code) and their data
- How does SFI work?

SFI Policy


Fault Domain
CB
CL
DB
DL
Code Region (readable, executable)
Data Region (readable, writable)
1) All jumps remain in CR
2) Reference monitor not bypassed by jumps
All R/W remain in DR [DB, DL]

Take Away

- Reducing vulnerabilities is the target of defenses
- We can reduce flaws
  - But, need help in validating safe cases and/or identifying cases helpfully – e.g., analysis
- We can limit accessibility to flaws further
  - Attack surfaces and privilege separation
- We can reduce the ability of adversaries to exploit the remaining flaws
  - May be a bit expensive w/o hardware help or need to be more targeted