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CRASH-WORTHY TRUSTWORTHY SYSTEMS RESEARCH AND DEVELOPMENT

Secure Linking in the CheriBSD Operating System

Alexander Richardson, Robert N. M. Watson

University of Cambridge

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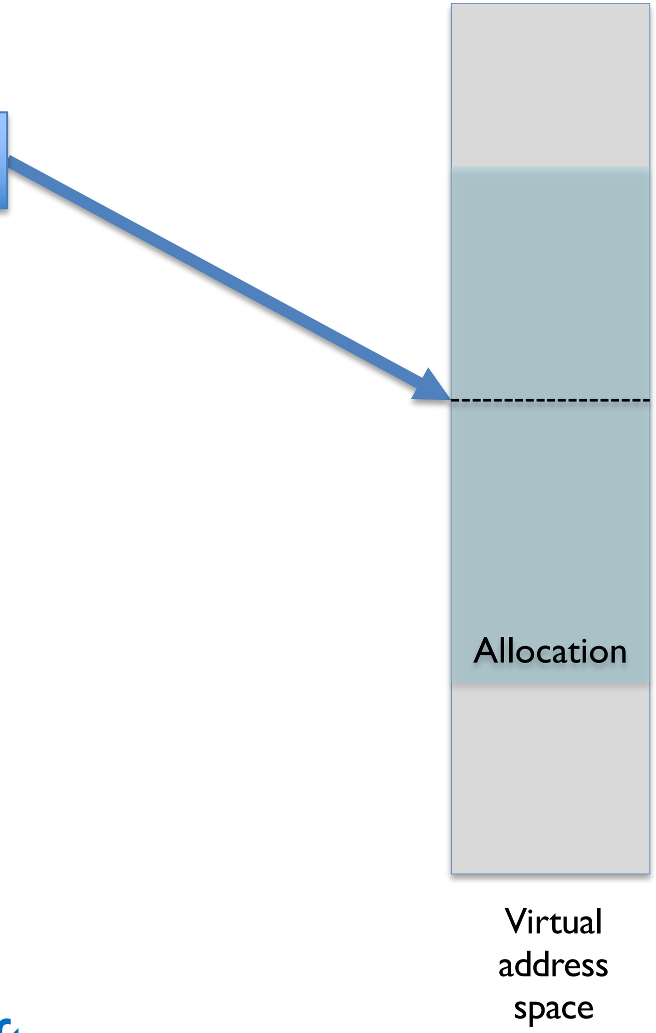
Outline

- A little about the CHERI architecture
- What do we mean by secure linking in the CHERI context?
- CHERI pure-capability protection before secure linking
- Improvements made by secure linking
- What more could be done?

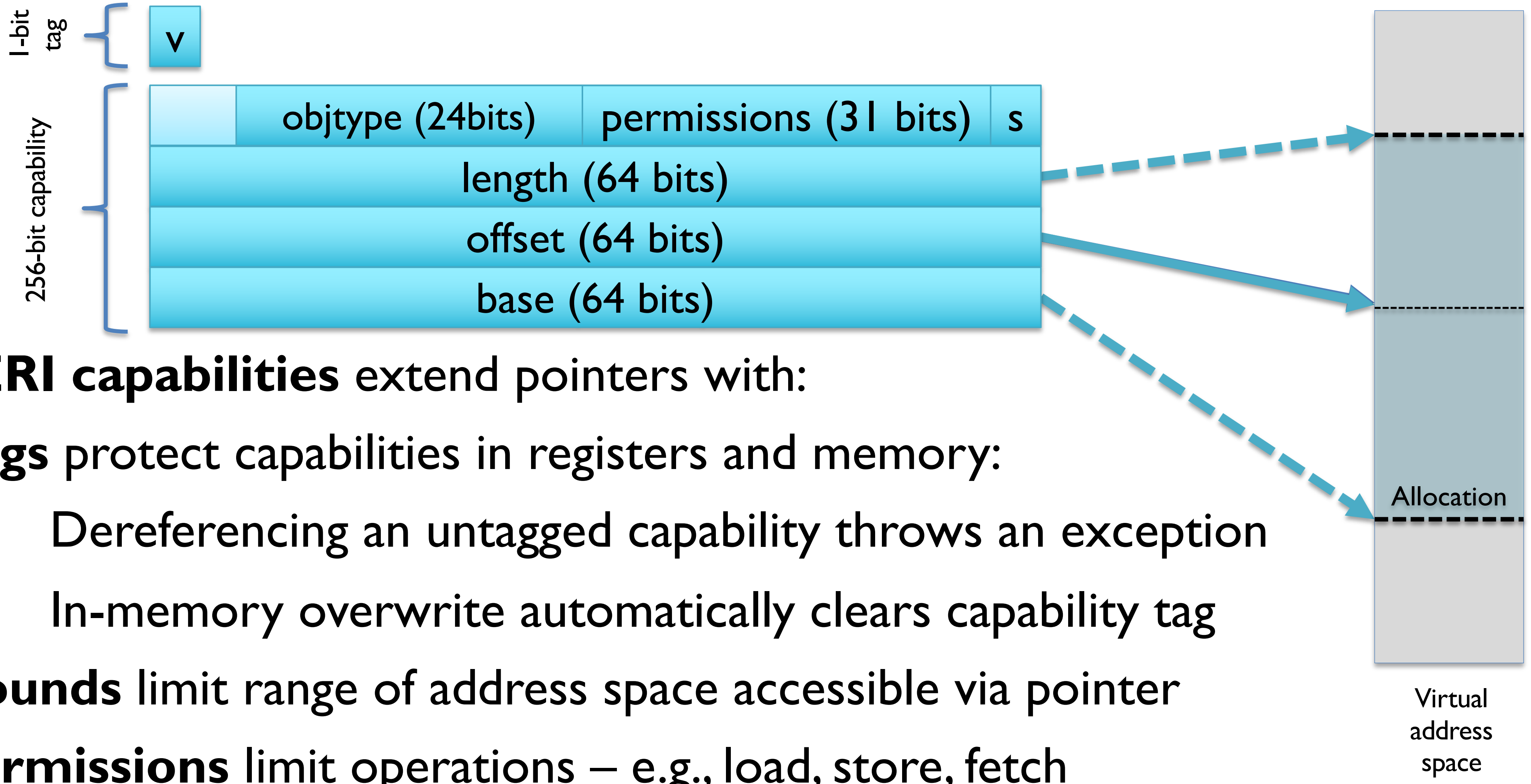
Pointers today



- Implemented as **integer virtual addresses (VAs)**
- (Usually) point into **allocations**, **mappings**
  - **Derived** from other pointers via integer arithmetic
  - **Dereferenced** via jump, load, store
- **No integrity protection** – can be injected/corrupted
- **Arithmetic errors** – out-of-bounds leaks/overwrites
- **Inappropriate use** – executable data, format strings

➢ Attacks on data and code pointers are highly effective, often achieving **arbitrary code execution**

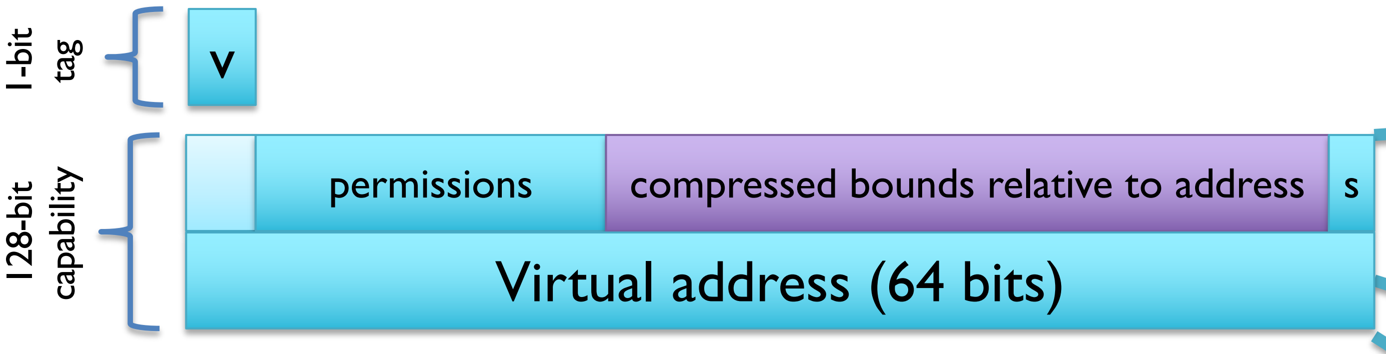
Protection model: 256-bit capabilities



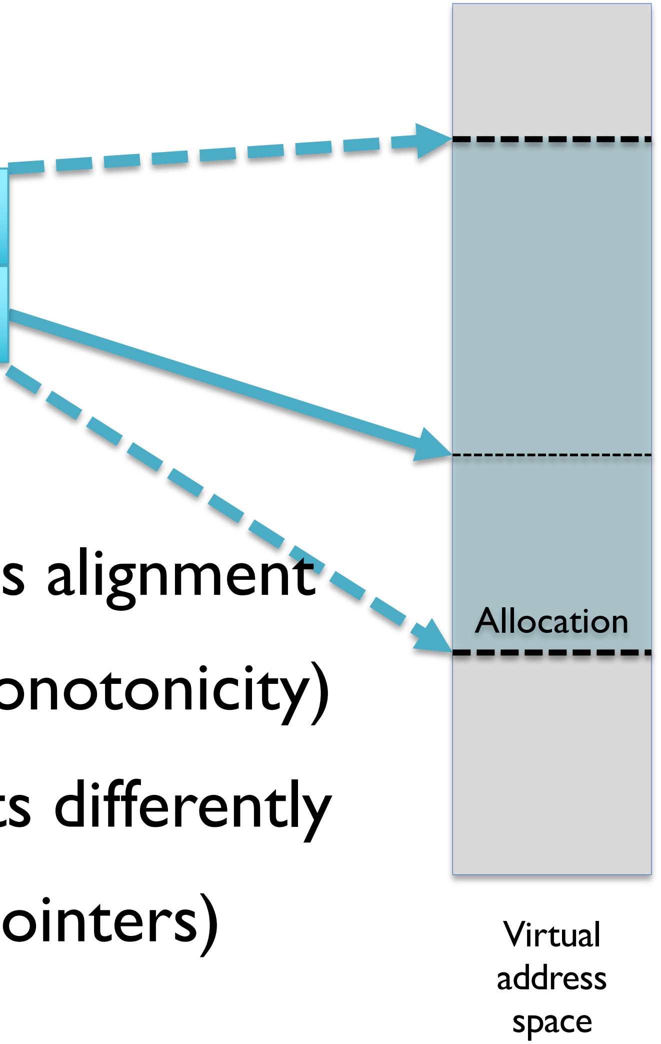
CHERI capabilities extend pointers with:

- **Tags** protect capabilities in registers and memory:
  - Dereferencing an untagged capability throws an exception
  - In-memory overwrite automatically clears capability tag
- **Bounds** limit range of address space accessible via pointer
- **Permissions** limit operations – e.g., load, store, fetch
- **Sealing** for **encapsulation**: **immutable, non-dereferenceable**

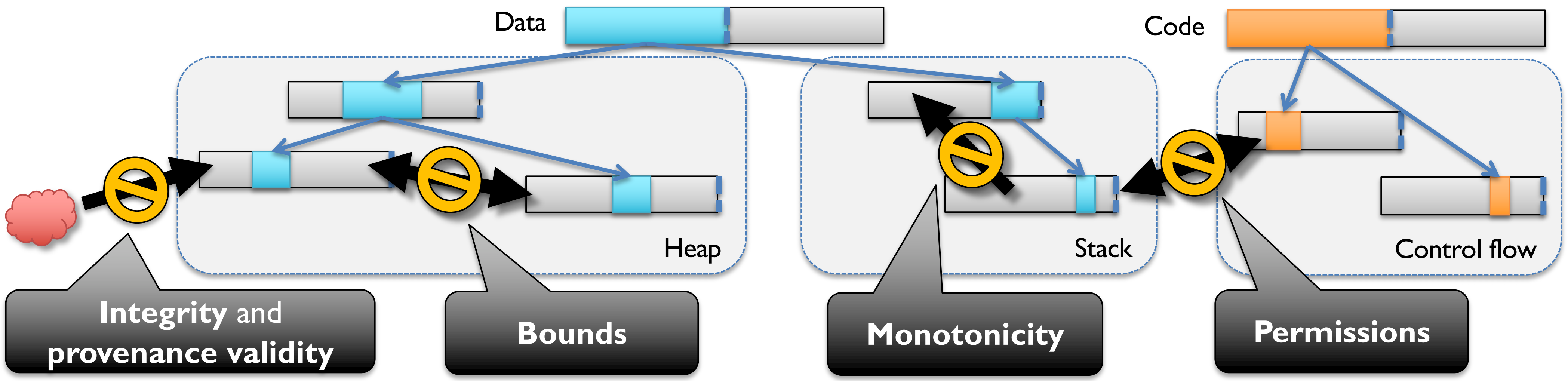
Architecture: 128-bit compressed capabilities



- **Compress bounds** relative to 64-bit virtual address
  - Floating-point bounds mechanism constrains bounds alignment
  - Security properties maintained (e.g., provenance, monotonicity)
  - Formats for sealed, non-sealed capabilities invest bits differently
  - Strong C-language support (e.g., for out-of-bound pointers)



CHERI enforces protection semantics for pointers



- **Integrity** and **provenance validity** ensure that valid pointers are derived from other valid pointers via valid transformations; **invalid pointers cannot be used**
- **Bounds** prevent pointers from being manipulated to access the wrong object
- **Permissions** limit unintended use of pointers; e.g., W^X for pointers
- **Monotonicity** prevents pointer privilege escalation – e.g., broadening bounds

➢ However, bounds and permissions must be **initialized correctly** by software – e.g., stack allocator, heap allocator, **dynamic linker**

Example: protection for global variables

```
int x;

int y;

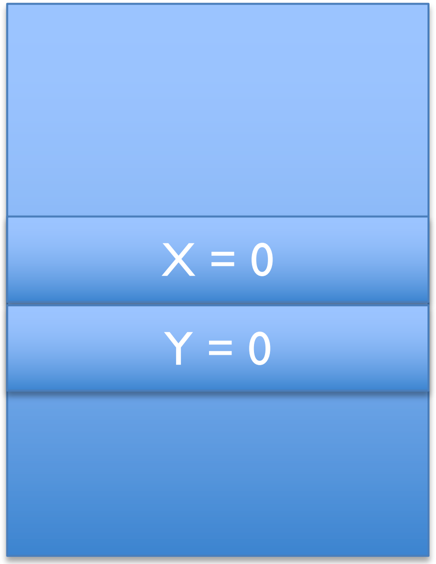

int main(int argc, char** argv) {

  int *ptr = &x;
  *ptr = 1;   // this is fine





}
```



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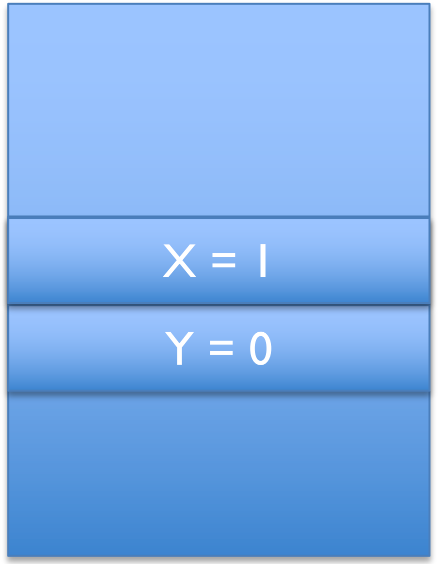

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  // address is the same as &y
  int *ptr2 = &x + 1;
  *ptr2 = 2; // what happens here?
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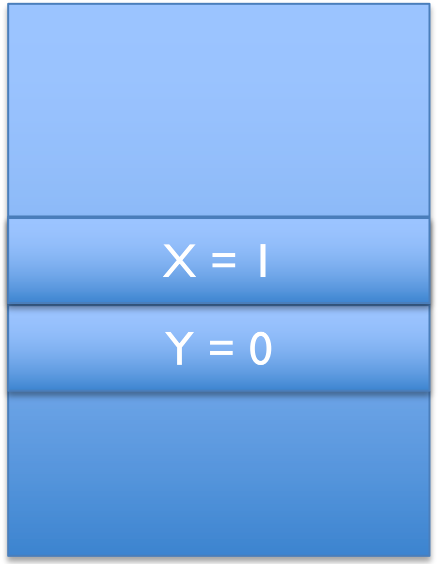
```



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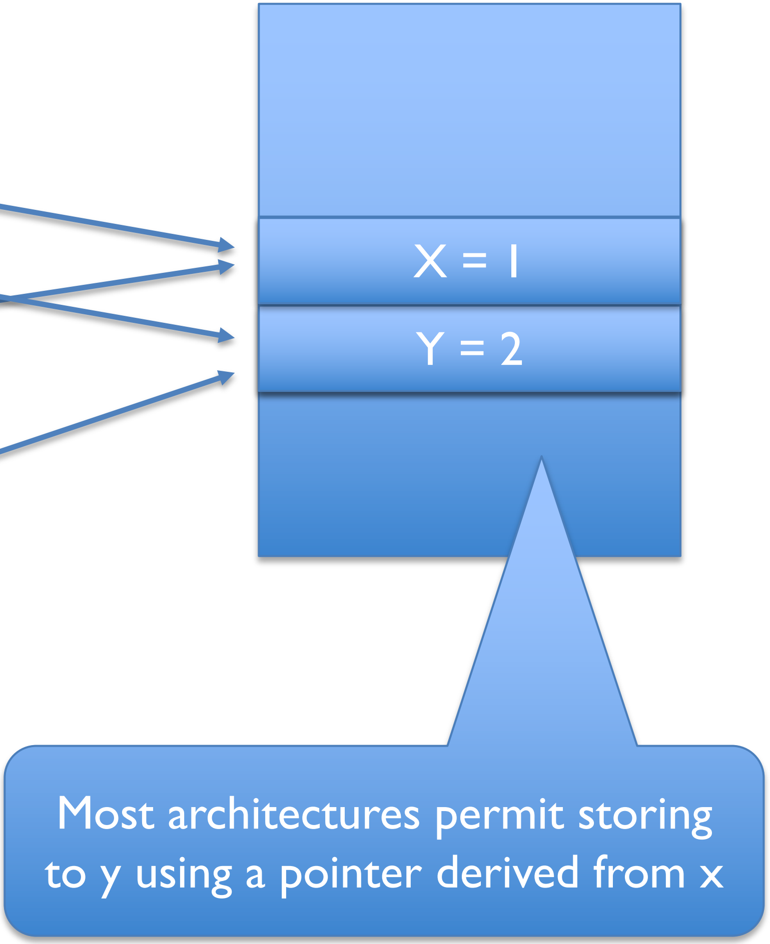

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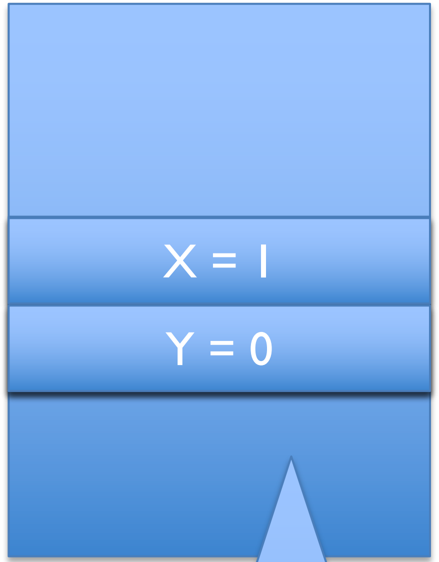


Using CHERI we can ensure that a write to y via a pointer to x always fails.
If the initial bounds were set correctly

Most architectures permit storing to y using a pointer derived from x

Overall goal: **reducing available privilege**

- By privilege we mean the **memory accessible at a given time** in the program's execution
  - For now we ignore file system and network access rights. This kind of sandboxing can be managed differently (e.g. by using Capsicum)
- In a conventional architecture privilege is all memory **mapped as accessible by the MMU**
  - **Every integer is also a valid pointer** and can therefore be used to access memory.
  - ASLR makes arbitrary accesses more difficult but does not prevent them.
- With CHERI privilege is the set of **all capabilities transitively reachable** from the current register contents.
  - The **MMU can further restrict** accessible memory (but is not essential).
  - The CheriBSD kernel ensures that memory management APIs can't break capability monotonicity.

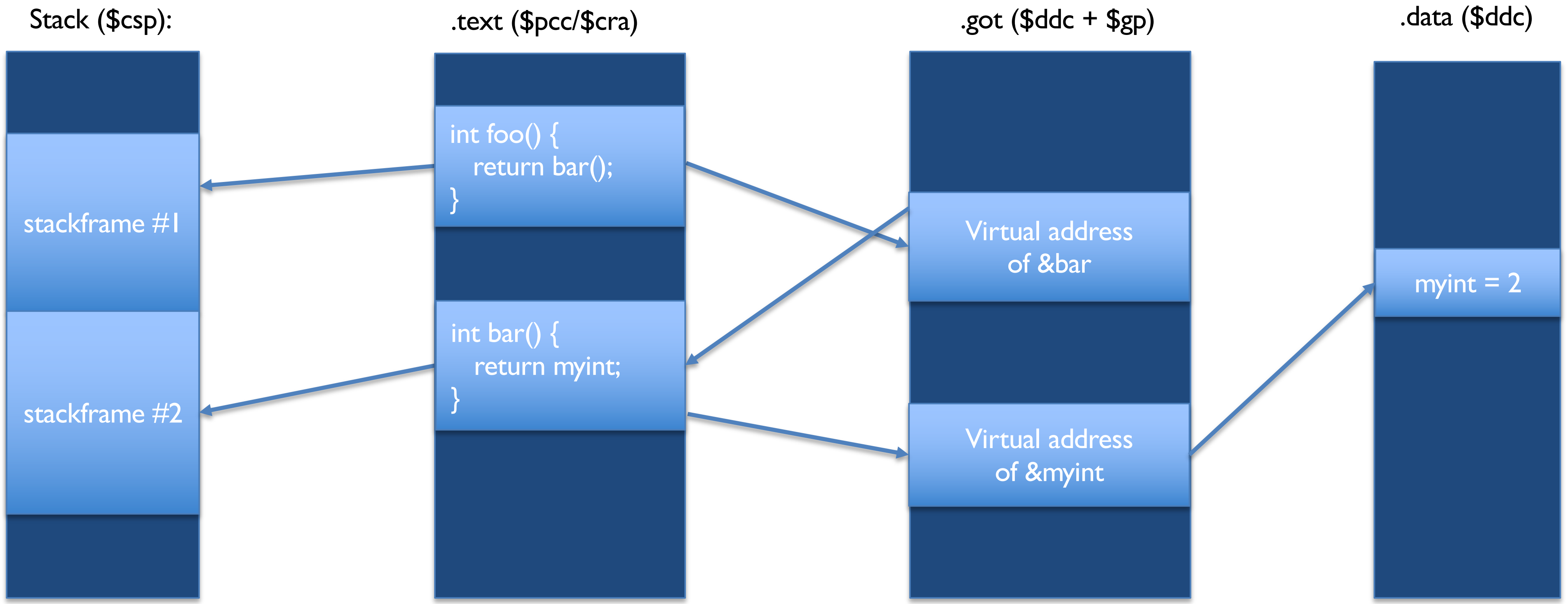
CHERI pure-capability linkage design goals

By reducing the amount of privilege available, we can achieve the following:

- **Completely eliminate out-of-bounds memory accesses for global variables**
  - Memory outside of the current DSO should be inaccessible (except for exported symbols)
- **Even stronger protection against control-flow hijacking**
  - CHERI hardware already prevents arbitrary jumps
  - Linker support can reduce the number of accessible code capabilities
- **Reduce the size of the TCB**
  - Compiler code-generation bugs can't break the overall security model since we don't rely on compiler-inserted checks
  - However, compiler and static linker are **partially trusted** to create an ELF file with a valid symbol table and relocations to be processed by kernel ELF loader and dynamic linker
  - Only the runtime linker and the kernel should are fully trusted but not libc.so, etc.

CHERI pure-capability code without secure linkage

- Capabilities to global variables are derived by using the virtual addresses from the GOT as an offset into **program counter capability ($pcc)** or **default data capability ($ddc).**
- MIPS globals pointer ($gp) used to find GOT by indexing into $ddc.



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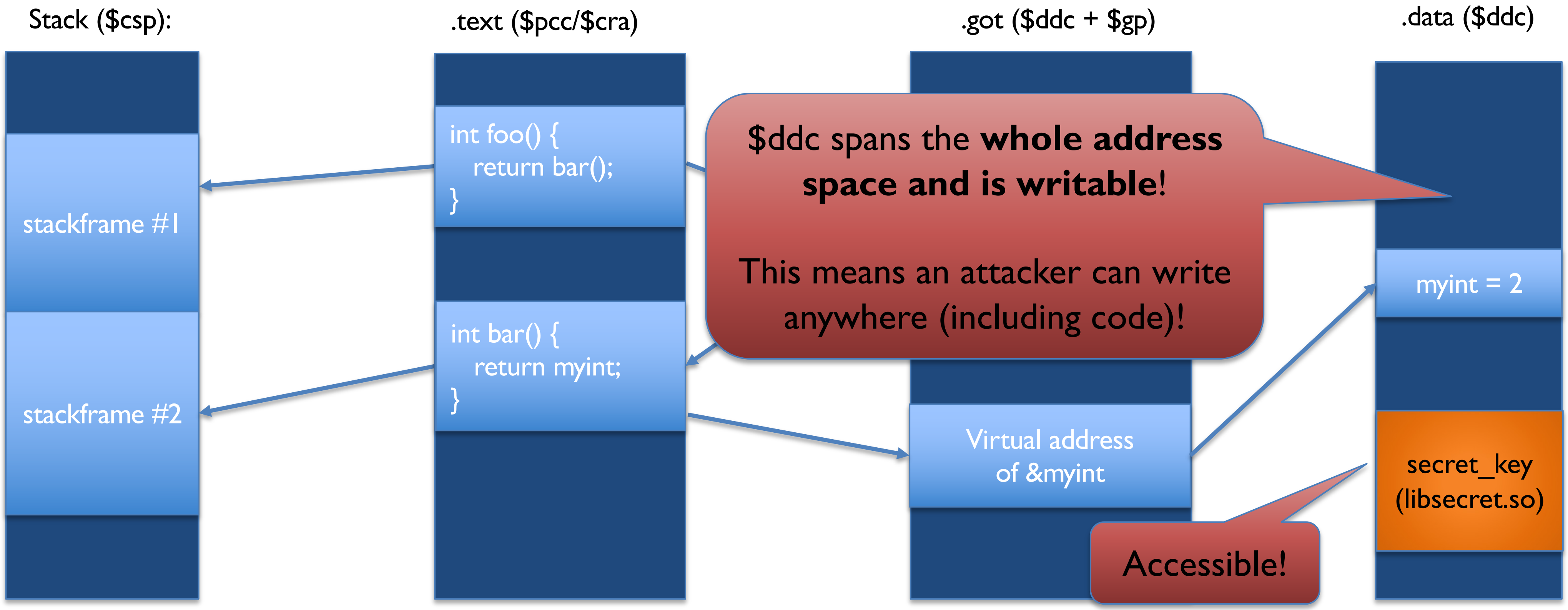

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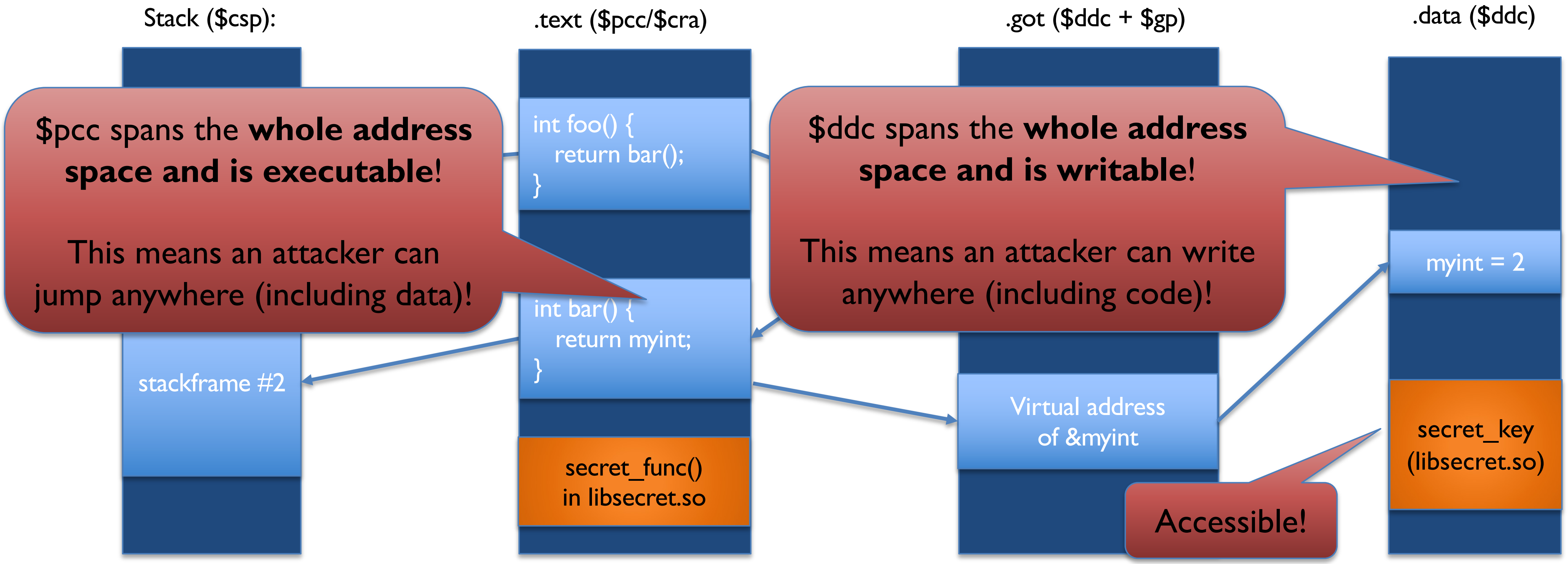


Bounds on global variables without linker support

- Capabilities to global variables are derived by using the virtual addresses from the GOT as an offset into $ppc or $ddc
- Bounds on global variables are implemented in the compiler by adding CSetBounds instructions for global variables as is done for stack allocations
  - The executing code still has access to ambient capabilities that need to be bounded correctly → compiler code generation bugs can result in excessive privilege
  - Furthermore, this only works if the size of a variable is known
  - Can use various hacks to almost make it work for external symbols
- This model (mostly) works but has various limitations

Accessing global variables with linker support

- Existing architectures can just generate any integer value and use that to access a variable.
  - This is not possible with CHERI due to monotonicity and integrity.
- Alternatively they can add a constant to $pc/$gp/toc/etc. in the PIC case (which must be within bounds for CHERI).
- For CHERI all global variable accesses and function calls must load an authorizing capability from a GOT-like table (the **captable**) even for position-dependent code.
- The static linker emits relocations to initialize capabilities in the globals table that are processed by the runtime linker on program startup.
  - All capabilities must be initialized anyway because non-RAM storage cannot save tags. This initialization is equivalent to relocating pointer values by the load address in PIE.
  - PIE increasingly the default for ASLR so **this adds no new overhead** from CHERI compared to commonly on by default vulnerability mitigation techniques.

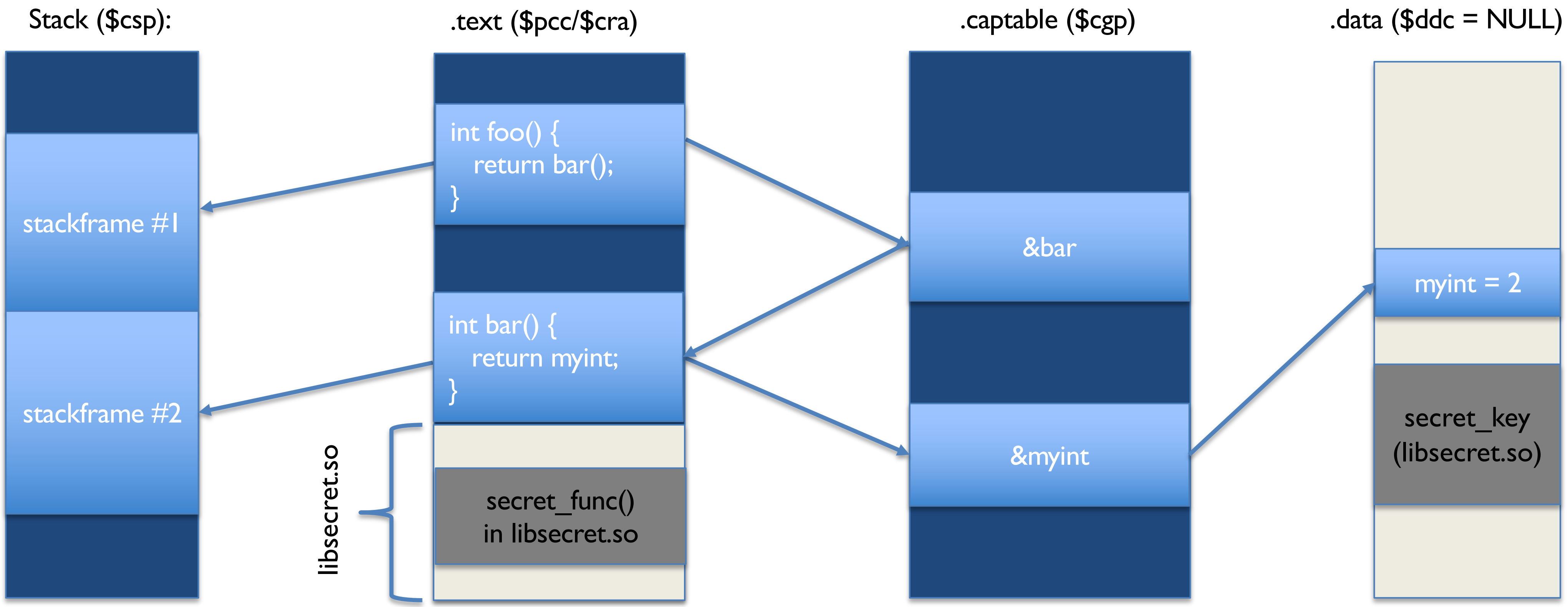
➢ Every function needs a **capability for the globals table ($cgp) on entry**

PC-relative linkage model

- **$cgp** is generated by **adding a static link-time constant to $pcc.**
  - This means **$ddc can now be NULL.**
- **Advantages**:
  - $cgp can be generated within function so no need to pass as it as an (implicit) argument.
    - This means function pointers can point directly to the function and do not need a trampoline that generates $cgp
  - Very similar to existing MIPS code generation (same number of instructions). Therefore a good model for fair benchmarks between pure-capability and legacy MIPS code
  - More efficient in contemporary architectures with pc-relative loads/AUIPC
- **Disadvantages**:
  - $pcc must grant access to both the current function and the table of capabilities (i.e., .text and .captable section) and requires at least LOAD_DATA and LOAD_CAP permissions on $pcc
  - An attacker with arbitrary code execution could jump to any instruction within the current DSO

PC-relative linkage model

- All privilege held in three registers: **stack pointer ($csp)**, **program counter ($pcc)** and **return capability ($cra).** The **globals pointer ($cgp)** is generated from $pcc.
- Since **$ddc is now NULL** only globals listed in the captable are accessible.



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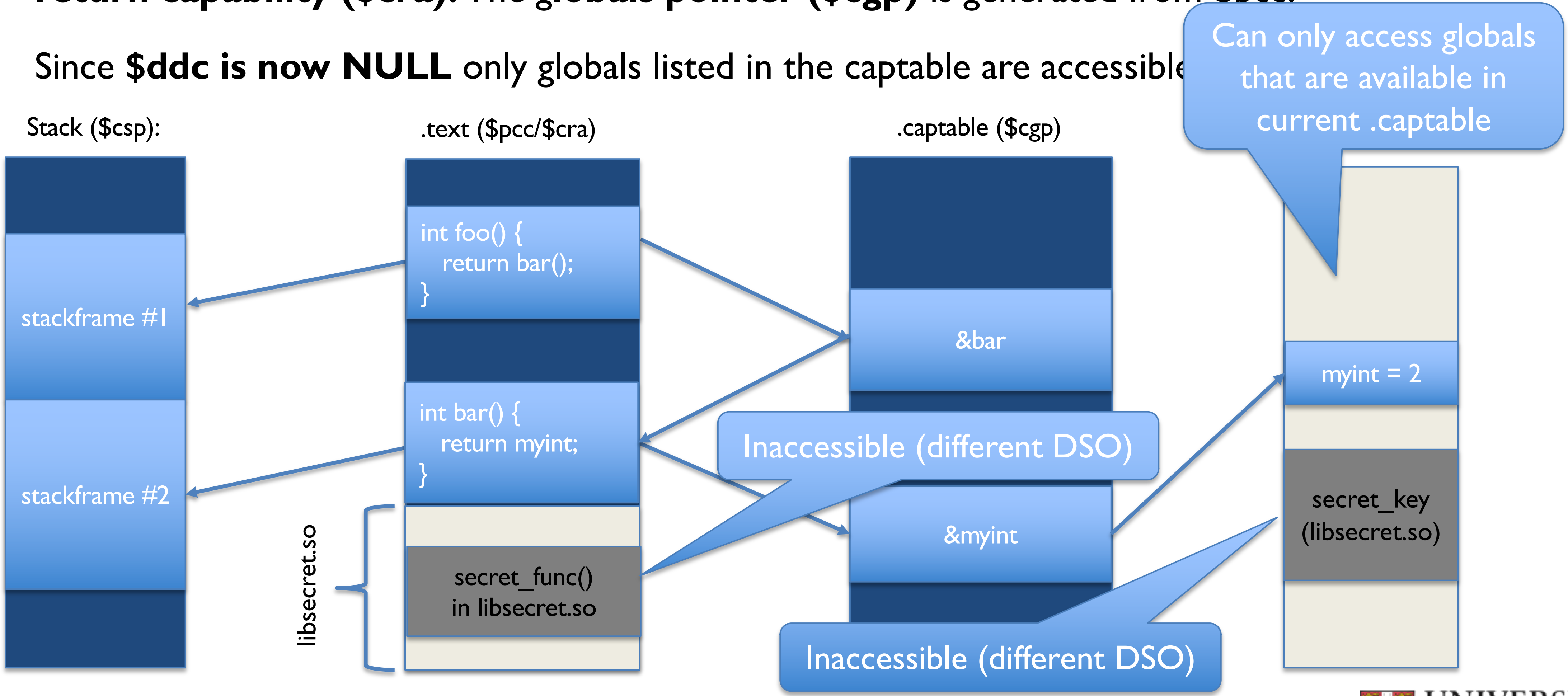

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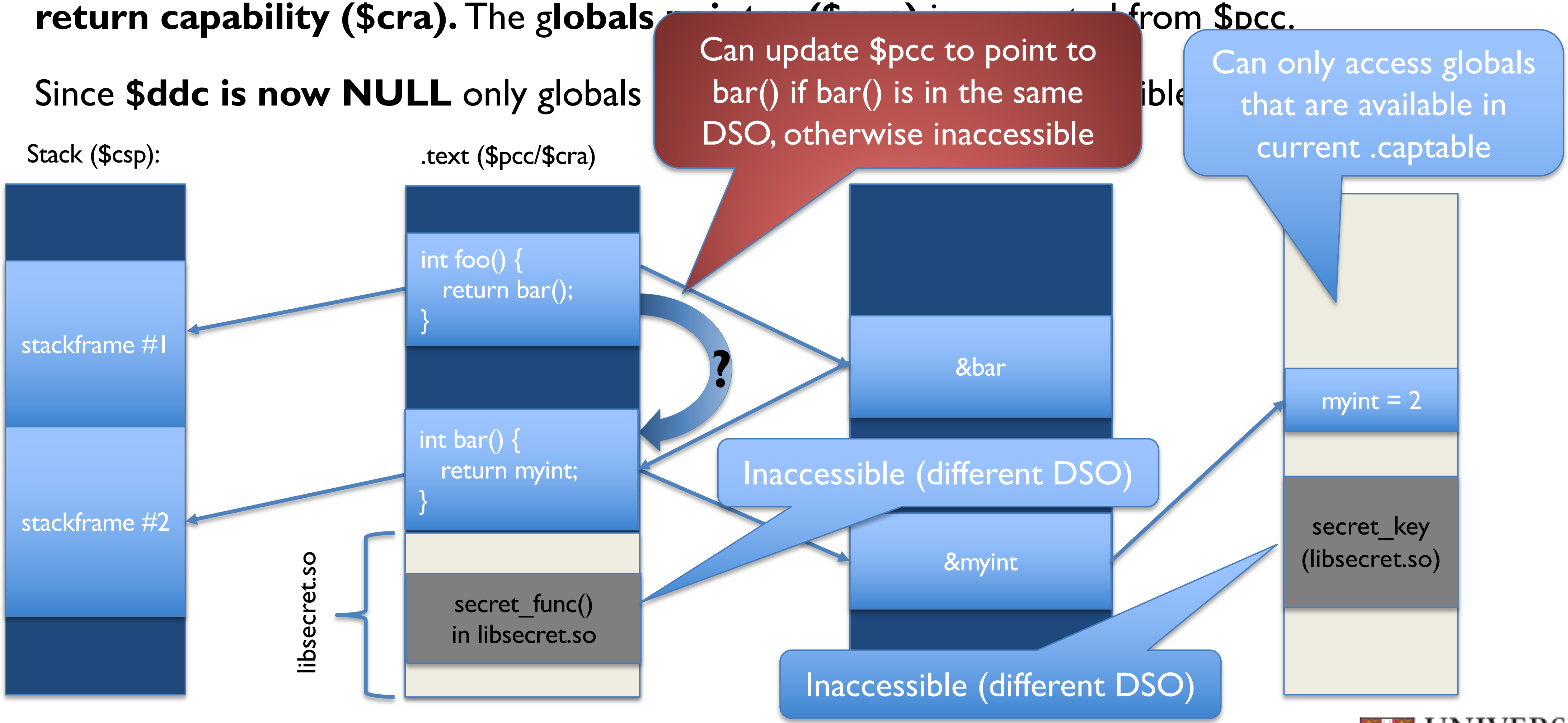

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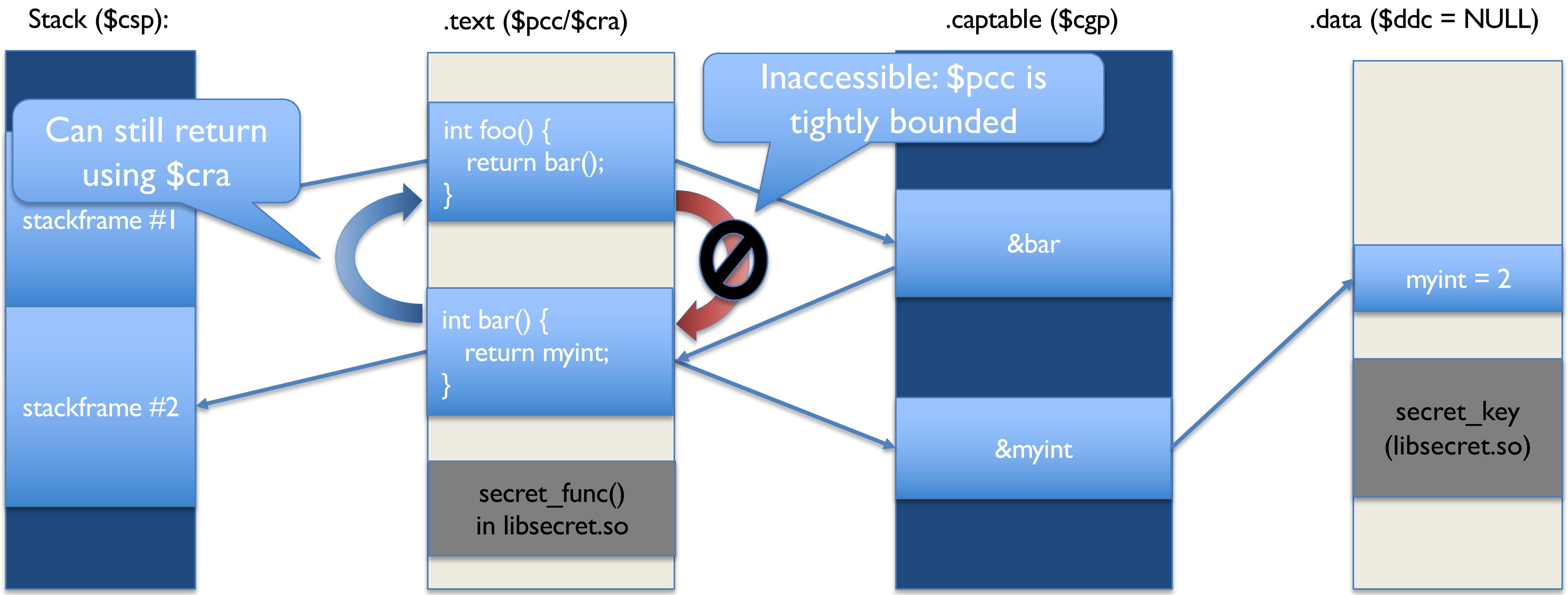
PLT linkage model

- **$cgp** must be **set correctly on function entry** and is a caller-save register
  - This value can remain the same for calls within a library
- **Advantages:**
  - Saves three instructions on function entry to generate $cgp
  - $pcc is bounded to the current function
  - An attacker with arbitrary code execution only has access to capabilities in the captable
- **Disadvantages:**
  - $cgp must be set correctly by the caller or a PLT stub (which adds four instructions including two memory loads)
  - Function pointers cannot point to the function but a trampoline that sets up $cgp
    - This is required to call from a context with a different $cgp (e.g., UNIX signal handlers).
    - This makes it harder to ensure they are ***globally unique*** (required by C standard).

PLT linkage model

- All privilege held in four bounded registers: **$csp, $pcc, $cgp** and **$cra**
- **$pcc is bounded to only the current function.**



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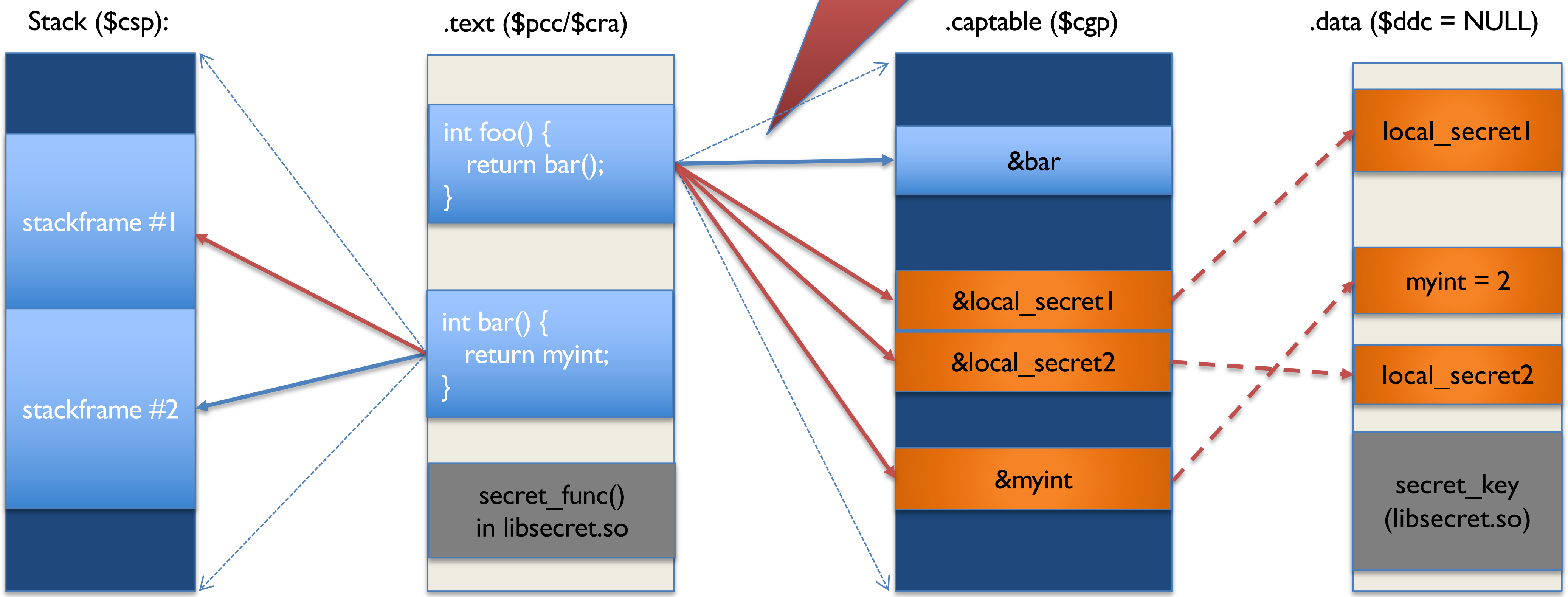
PLT linkage model

- All privilege held in four registers: **$csp, $pc**
- **$pcc bounded to only the current funct**

All globals in the .captable section are accessible!



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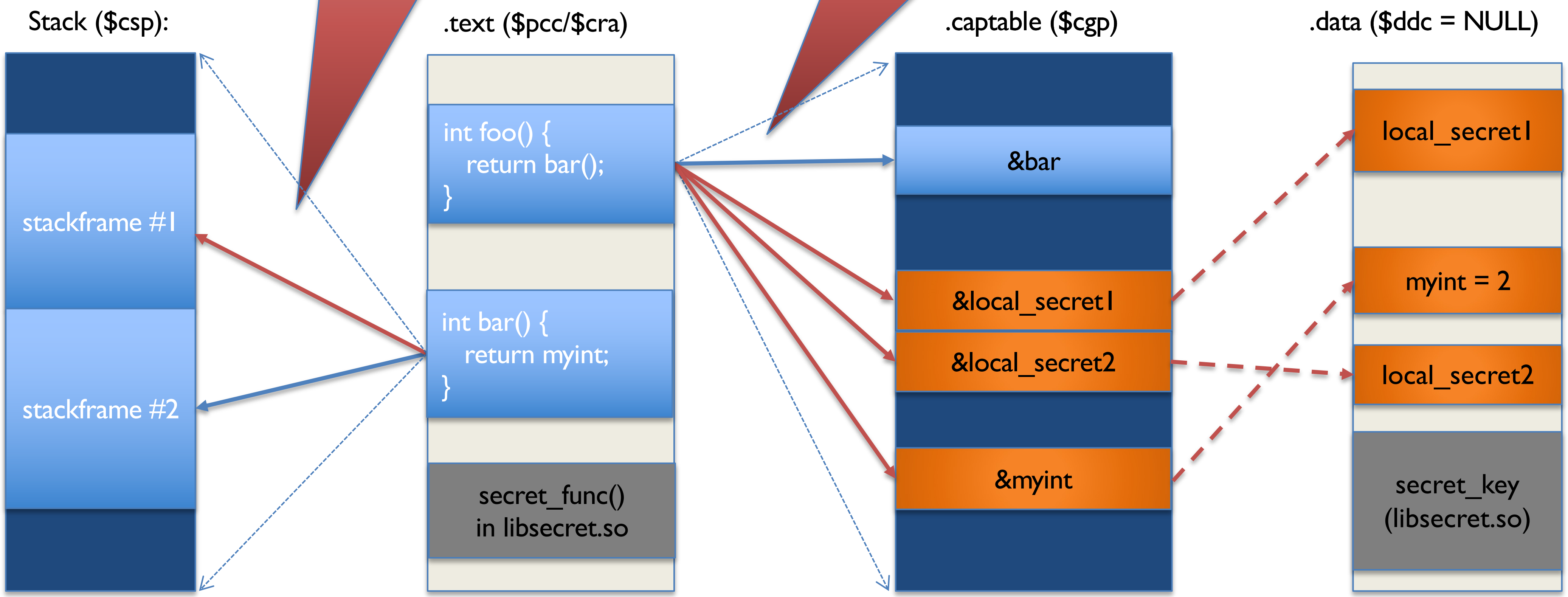
PLT linkage model

- All privilege h … $pc
- **$pcc bound … unct**

Called function can still access caller’s stack frame!

All globals in the .captable section are accessible!



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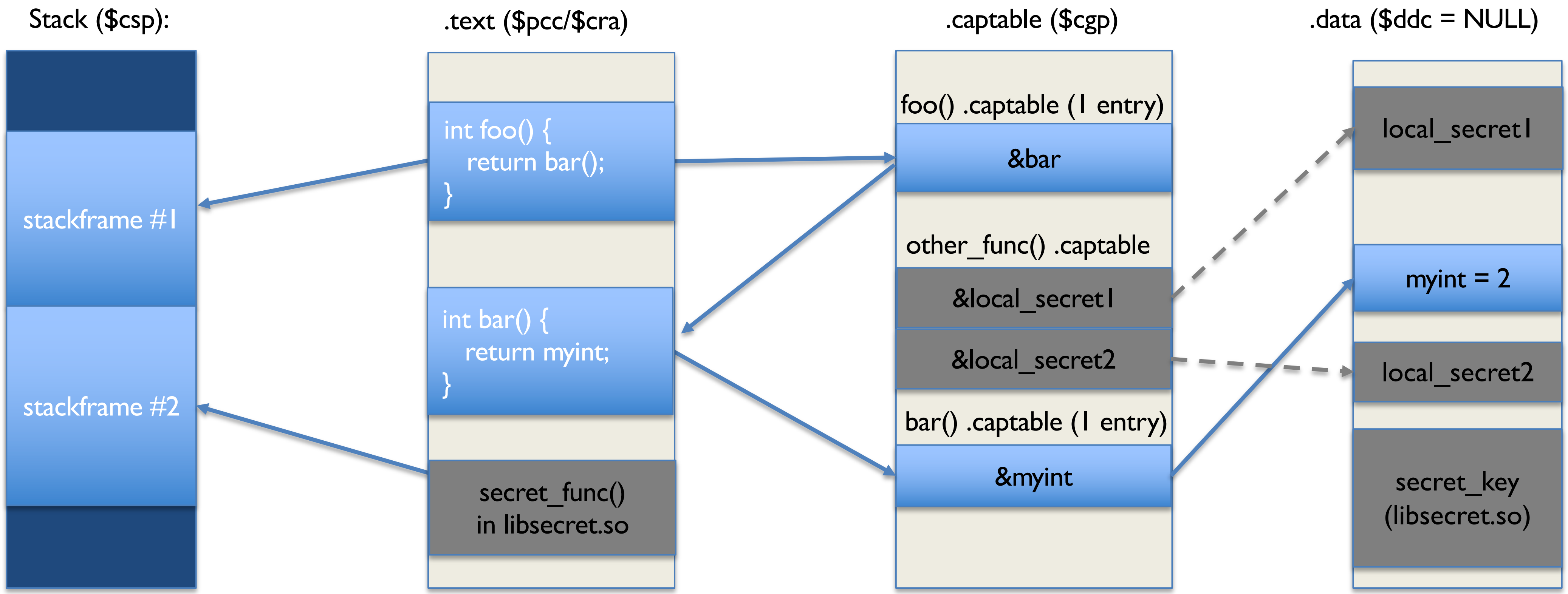
Per-function .captable

- Each function uses a different $cgp → Privilege granted by $cgp is now **minimal.**
- Variables used by other functions are **inaccessible.**



Per-function .captable

- How can we find the correct table?
  - Static linker emits all per-function/per-file tables and concatenates them in a single *.captable* section
  - Also emits a special special ELF section that contains a mapping from function address to required *.captable* subset
  - Run-time linker can use this section when creating PLT stubs for exported function or external calls
- Note: the run-time linker must also insert a PLT stub for every local call since every function needs a different $cgp value
- Per-function tables will result in duplicate capabilities in the *.captable*. Some deduplication is possible for functions using the same set of globals.

Beyond basic privilege reduction

- Every library transition stub uses a **return stub** instead of returning to the caller directly.
- This allows switching to a separate stack on function transitions (or bounding and clearing it).
- Could also clear non-argument registers or validate control flow.

```
void foo() {
    // …
    bar();
    // …
    return;
}
```

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→

PLT stub for bar()

- Load $cgp + target $pcc
- Save return $cra and return $csp
- Limit or allocate new stack for bar()
- Allocate return stub and set $cra

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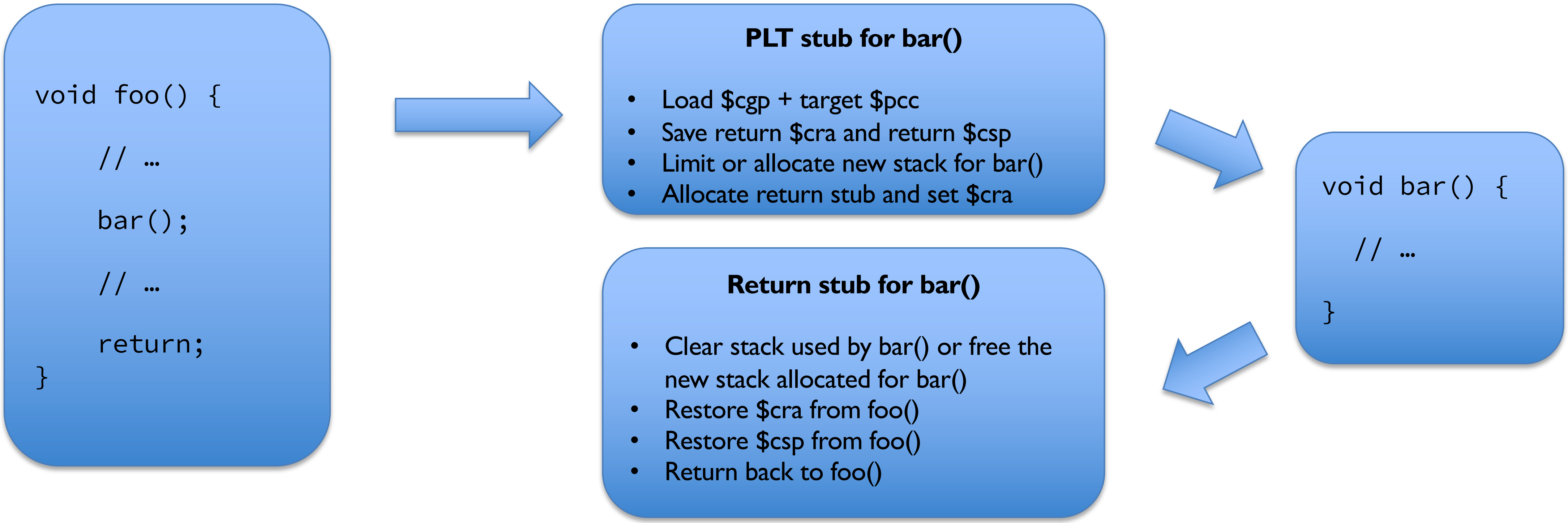

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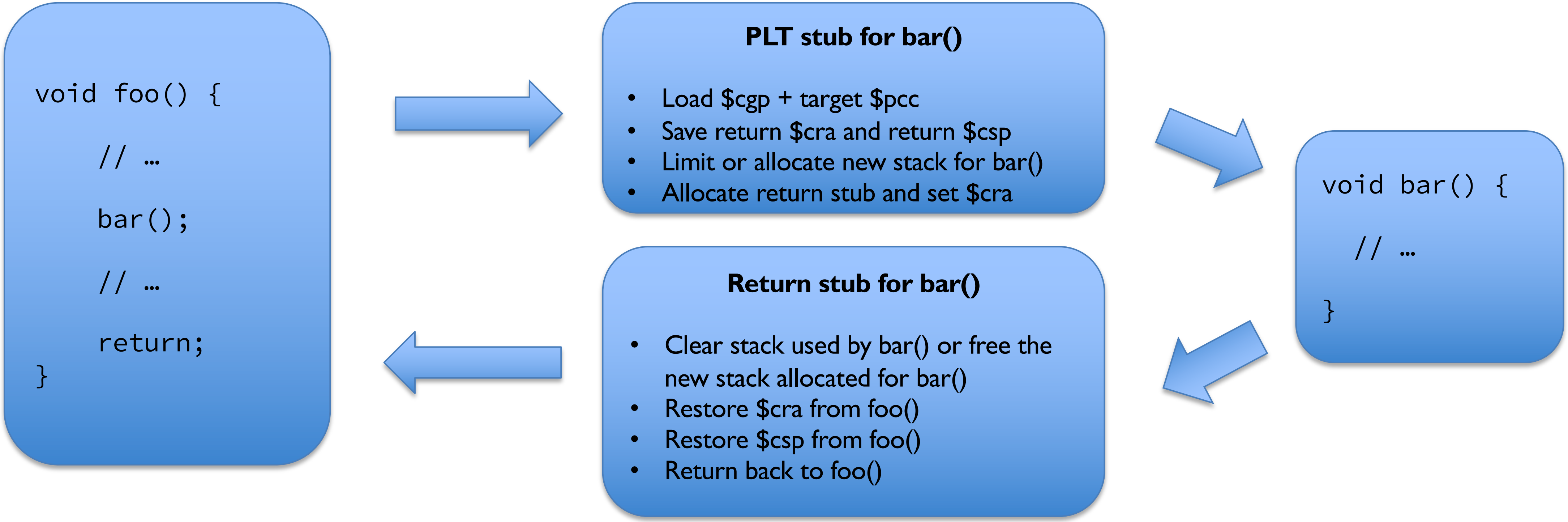


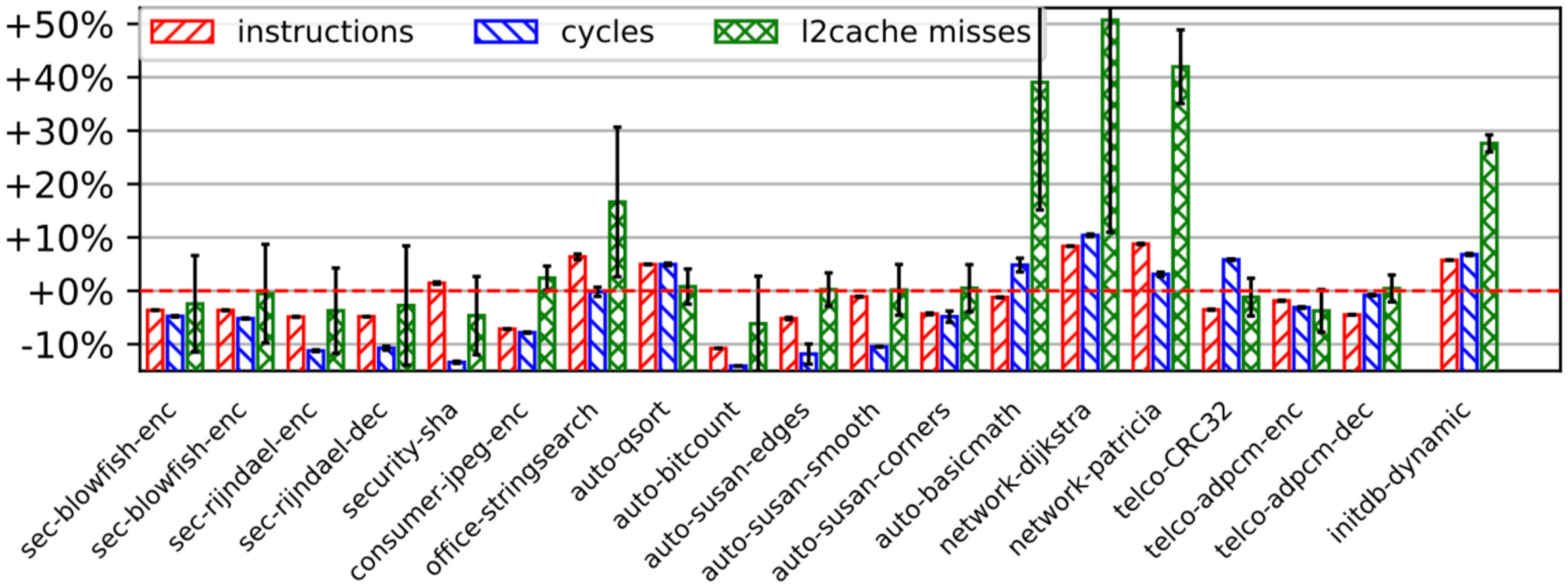
Configurable Linkage Policy

- PLT and return stubs are **dynamically allocated** by the runtime linker
- This allows flexible **policy decisions at link-time and at run-time**
- Runtime linker **supports mixing DSOs with different policies**
- We can therefore use different models depending on performance and security goals on a **per-library granularity**
- Linker and compiler flags can change available privilege scope:
  - General ABI selection: `-cheri-cap-table-abi={legacy,pcrel,plt}`
  - Further narrowing of captable scope (this only makes sense with the PLT ABI): `-Wl,-captable-scope={all,file,function}`
- RTLD can read a configuration file with per-library/binary policy:

```
/usr/lib/libsecure.so: new-stack,clear-regs
/usr/bin/more-speed-less-bounds: clear-regs
/bin/cat: trust-all
```

  - Basic infrastructure for this exists but not yet fully implemented

Performance (PC-relative ABI)



Impact commonly less than 5% (compared to MIPS)
PostgreSQL initdb 6.8%

Summary

- We fully support dynamic linking with minimal privilege including dlopen() and lazy binding.
- Compiler code-generation bugs cannot be exploited to gain access to inaccessible data.
- Further security goals such stack and register clearing to prevent data leakage can be enabled with a per-library configurable policy.
- It is possible to mix the different modes even within a process to choose a suitable trade-off between security and performance.
- All code is available on GitHub:
  - https://github.com/CTSRD-CHERI/llvm
  - https://github.com/CTSRD-CHERI/clang
  - https://github.com/CTSRD-CHERI/lld
  - https://github.com/CTSRD-CHERI/cheribsd
- To learn more about the CHERI architecture and prototypes:
  - https://www.cheri-cpu.org/

Questions?

What about loading via the target $pcc or $cra?

- In the current implementation this is still possible.
- However, this can be fixed by using the sealed capability mechanism.
  - Pairs of sealed capabilities can be invoked using CCall,
  - CCall unseals the paired capabilities (the data argument is unsealed into $cgp) and jumps to the code.
- We also have an experimental implementation of call-only sealed capabilities that could be used for call targets and return addresses.

Why don't we just use pairs of capabilities?

- We could do: by using **function descriptors**
- However, POSIX APIs require **`sizeof(void*) == sizeof(void(*)(void))`**
- Therefore we need indirection: function pointers are non-executable pointers to a pair of capabilities
- This is more-or-less the same as jumping to a stub that loads the pair
  - Can inline the pair in the captable, but this puts pressure on the limited immediate range in the load capability instruction
- Requires kernel changes to handle non-executable capabilities in `sigaction()`, etc.
- **Note:** We have an experimental function descriptor implementation with slightly different performance characteristics but the same security properties as the PLT model

Function pointers must be unique

- Required by C and C++ standard
- Cannot use the PLT stub as the function pointer since the stub is different in every library that uses that function.
- Chosen solution: The function pointer always resolves to a stub in the library that exports the function.
- Two different relocations for direct call and taking a function pointer:
  - R_MIPS_CHERI_CAPABILITY_CALL: does not need to be unique so can point to the per-DSO PLT stubs.
  - R_MIPS_CHERI_CAPABILITY: When used with STT_FUNC symbol guarantees a unique address (otherwise a direct data reference).
- Lazy binding is not possible for function pointers but still fine for direct calls.