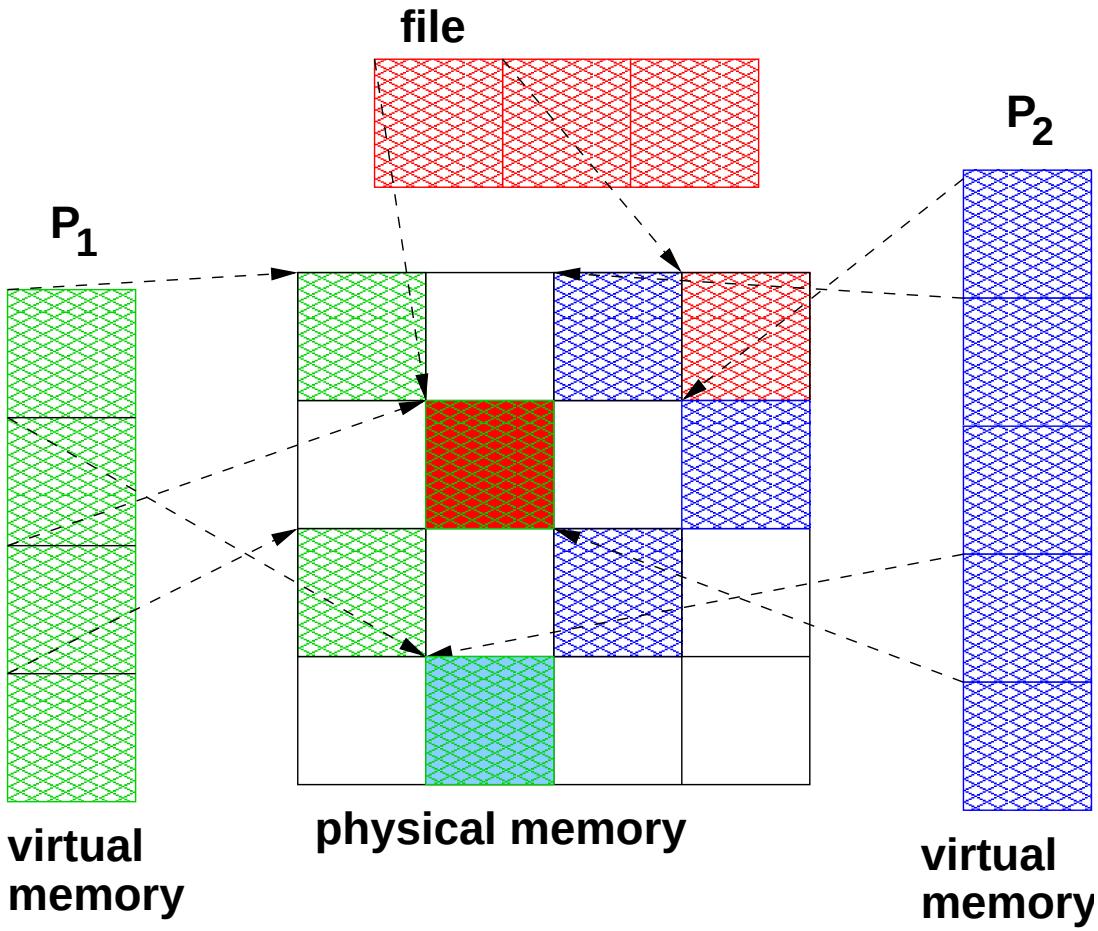
Single-Address-Space Operating Systems

- New paradigm for OS design
- Enabled by 64-bit hardware
- Motivation: use H/W features to:
  - ➜ improve overall performance,
  - ➜ simplify applications.

Address Spaces

Traditional OS use a separate address space for each process.



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- Drawbacks:
  - ➜ Meaning of virtual address depends on process context
  - ➜ Isolation inhibits sharing

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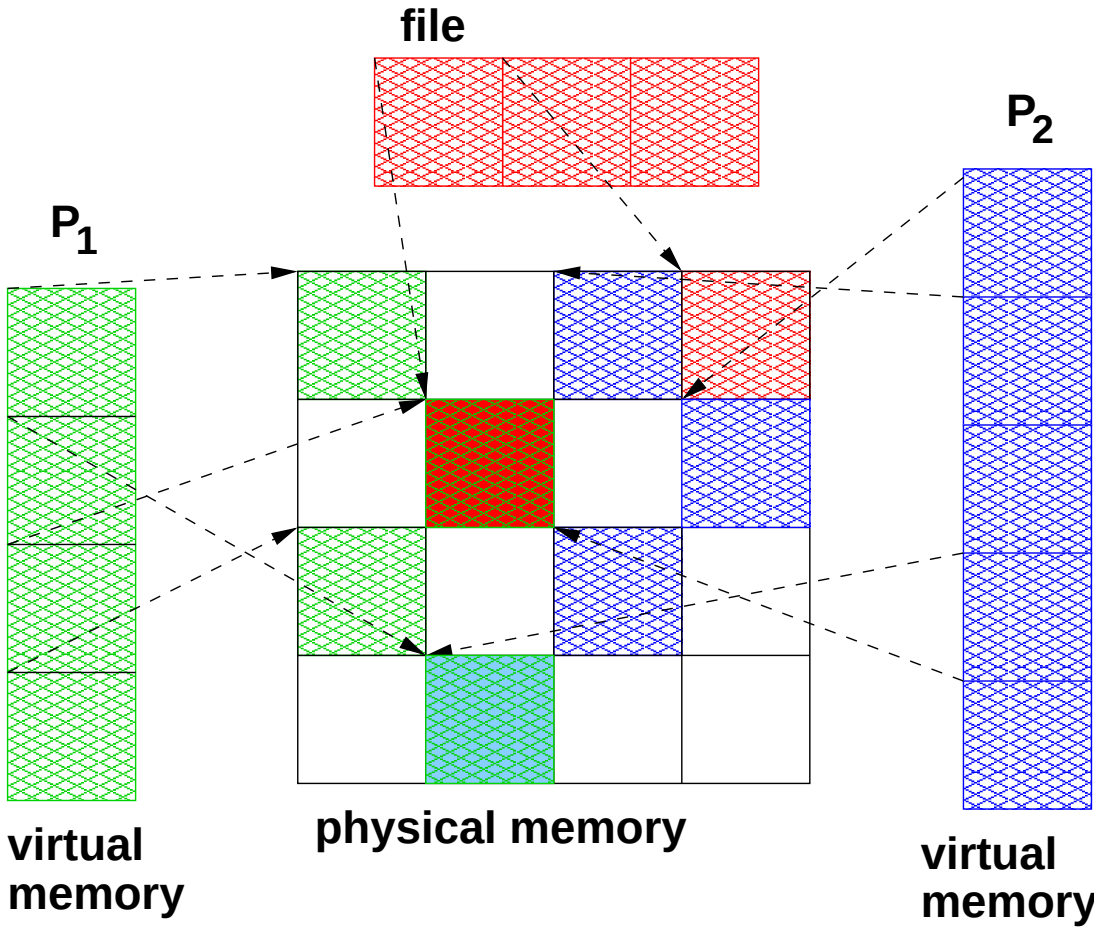
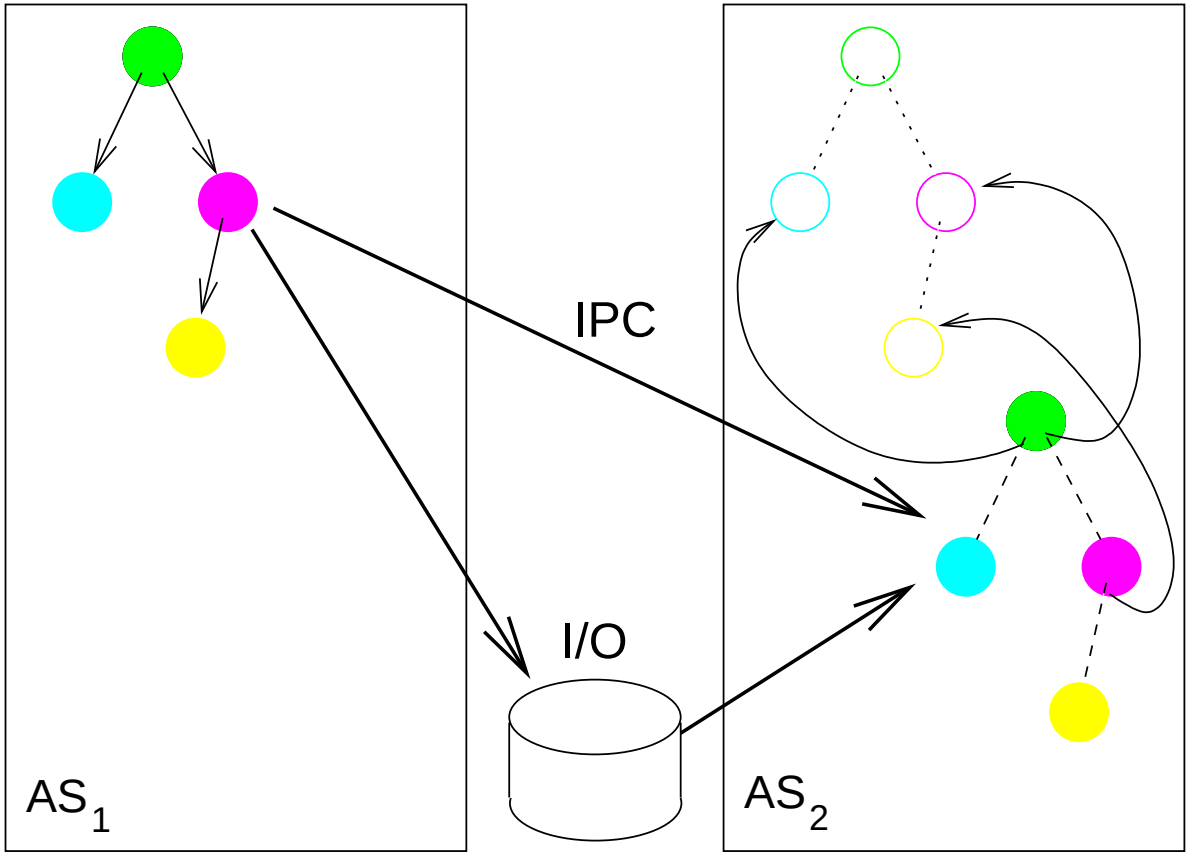
All require OS intervention.

SHARING BETWEEN ADDRESS SPACES



PROBLEMS WITH SHARING: POINTERS!



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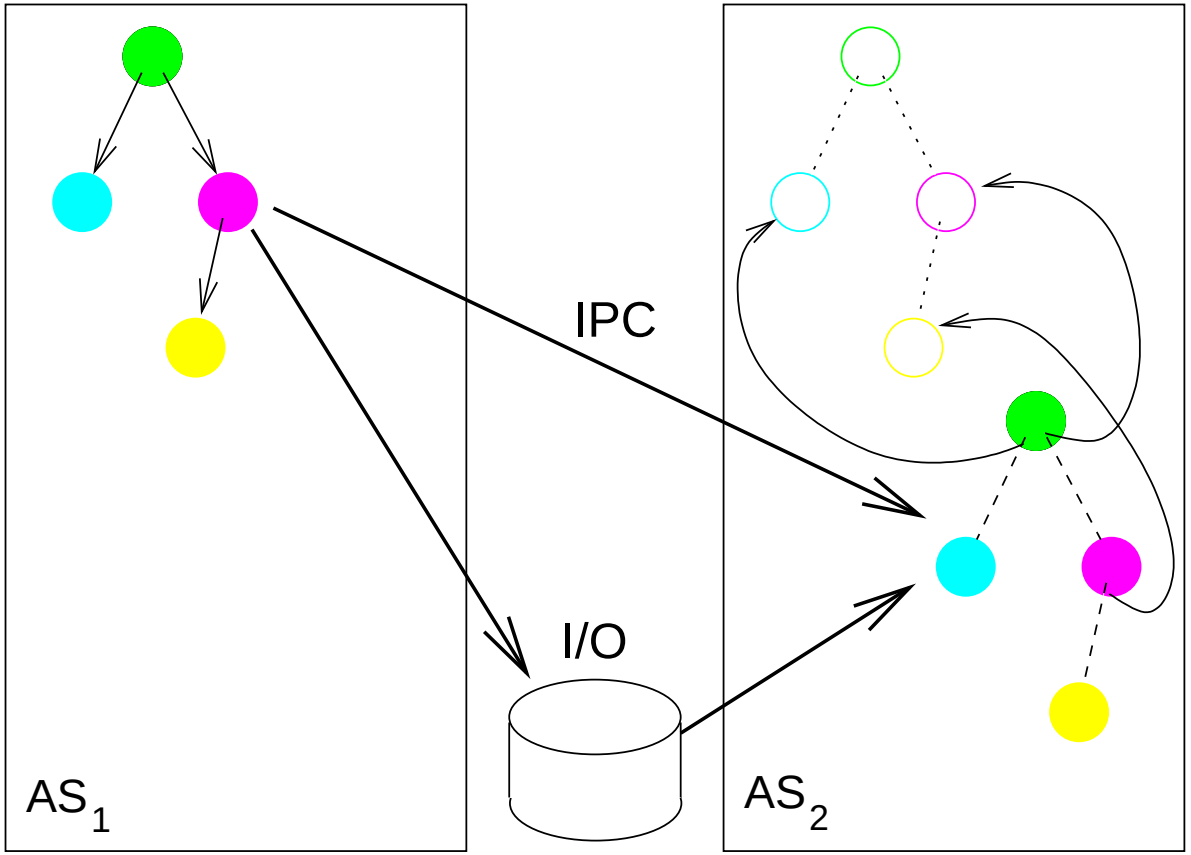

- ➜ pointers are bound to an address space
- ➜ they are meaningless outside

SHARING ACROSS ADDRESS SPACES

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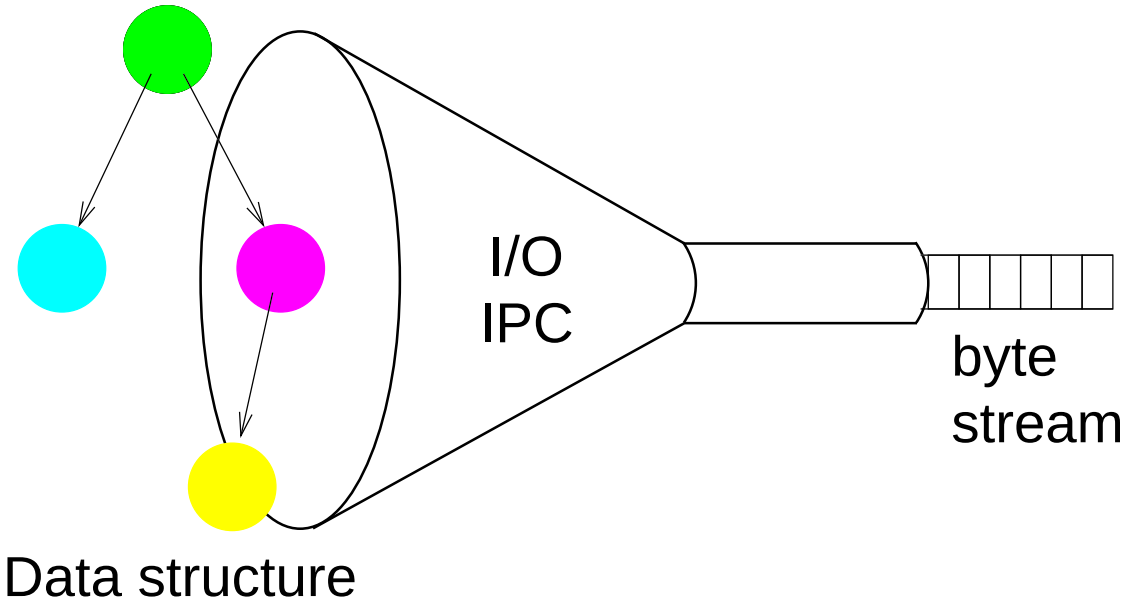

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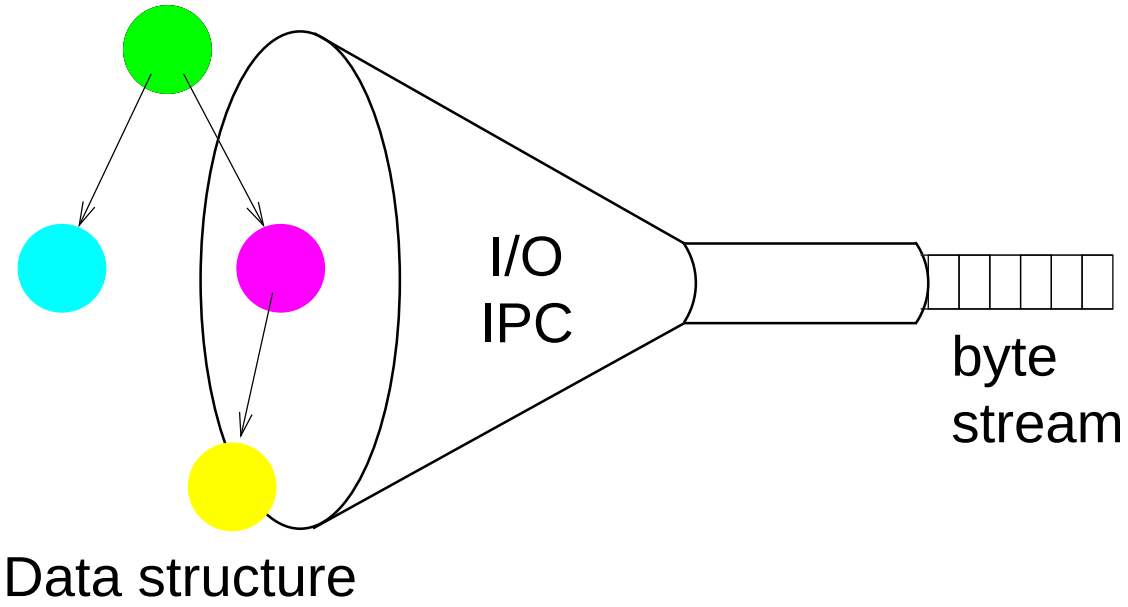

- ➜ implies loss of typing
- ➜ increases code complexity (order of 30% of app code!)
- ➜ increases run-time overhead

OTHER PROBLEMS WITH ADDRESS SPACES

memory data:

```
item_t a, *x;

...
a = *x;
```

address is `*x`

file data:

```
item_t a;
int    x;
FILE   *f;

...
f = fopen("f","r");
fseek (f, x, SEEK_SET);
fread (*a, sizeof(item_t), 1, f);
```

address is `("f",*x)`

Inconsistent naming of persistent and volatile data

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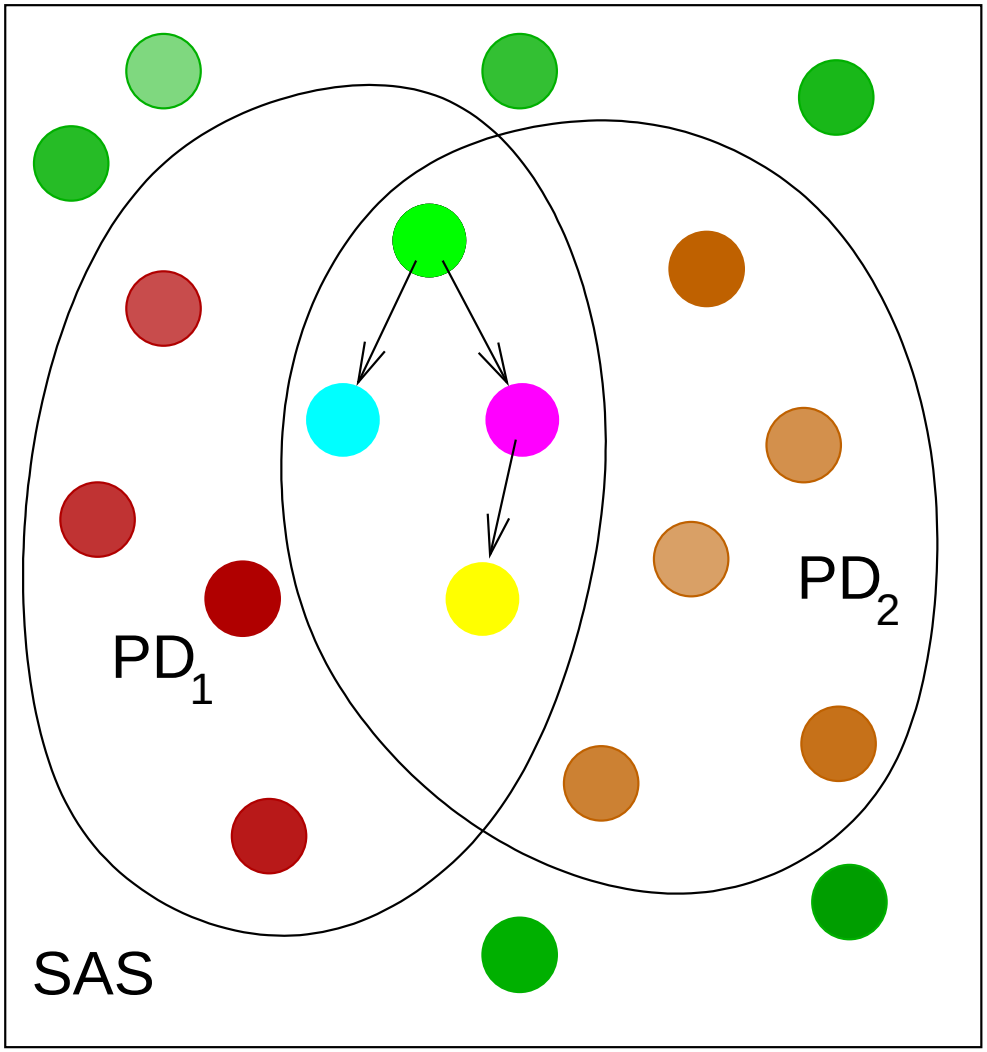
⇒ *single-address-space system*

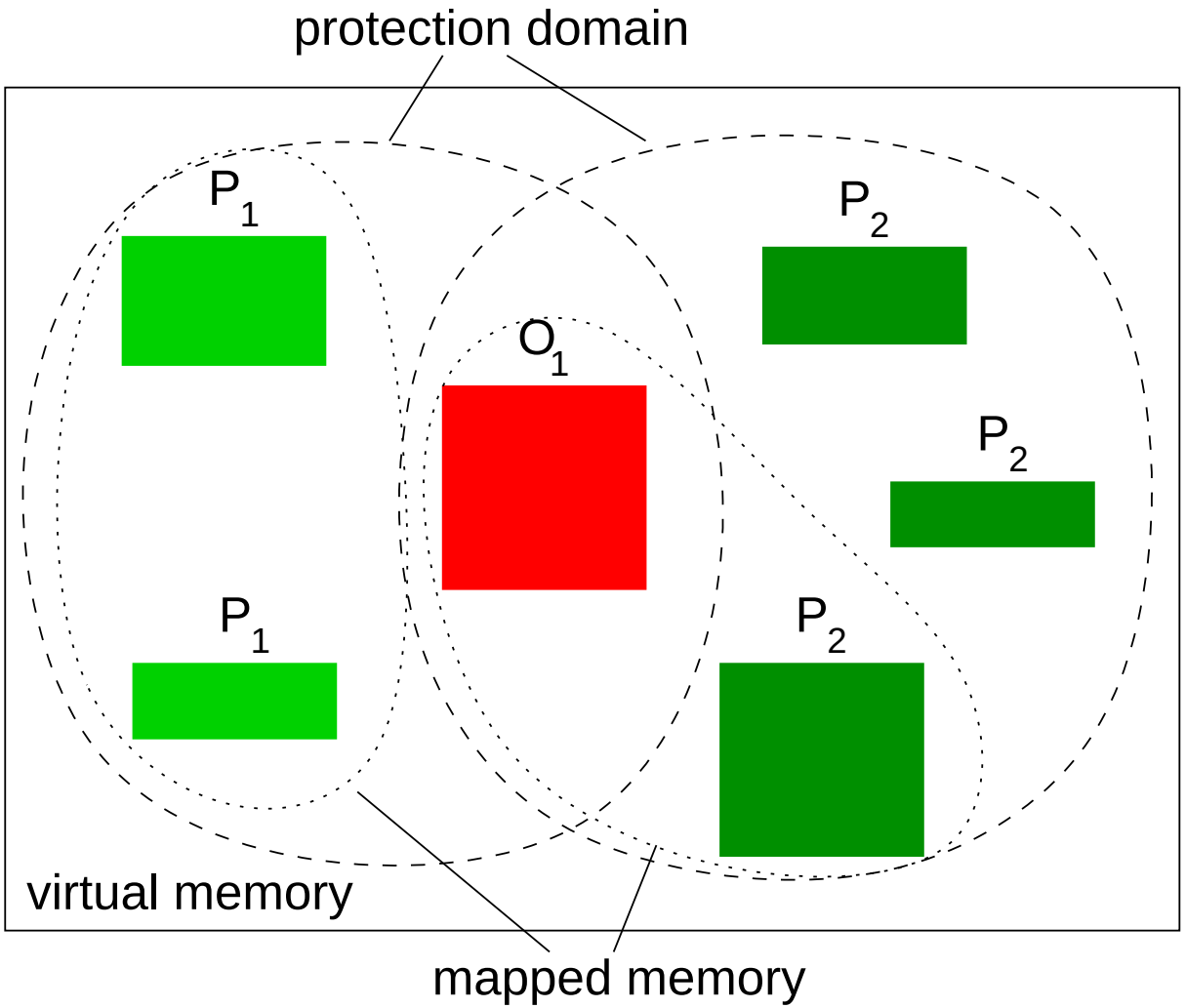
Single-Address-Space Operating Systems



SASOS CHARACTERISTICS:

- Unique addresses for all data items
  - ➜ threads always agree about the address of data
- Sharing by reference
  - ⋆ simply pass pointer
- no marshalling or conversion of data formats required
  - ➜ on-disk format same as in-memory format

Protection in a SASOS



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- Can implement usual protection models (ACLs, capabilities)

Single Address Space Advantages

APPLICATION VIEW

- Simple naming mechanism – 64 bit address – supported by “conventional” hardware.
- User data structures can contain embedded references to other data.
- Eliminates excessive copying of data and software pointer translation.

SASOS ADVANTAGES: SYSTEM VIEW

- Simplifies data migration
- Simplifies process migration
- Orthogonality of translation and protection
- No need for file system — all disk I/O is paging
- RAM is cache for VM — unified buffer & disk cache management
- Easy to implement zero-copy operations
- In-place execution — no need for position-independent code

$\Rightarrow$ Simplified system implementation and increased performance

SASOS Advantages: Hardware View

- Virtual caches are no problem
  virtual address maps uniquely to physical address

- Hardware separating translation from protection could increase performance due to increased TLB coverage
  (e.g. IA-64 *protection keys*)

Single-Address-Space Operating Systems

IBM SYSTEM/38 [Ber80] and successor **AS/400** [Sol96] (1978)

- high-level object-oriented architecture built on single-level store
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Drawbacks:

- ⋆ totally different environment
- ⋆ requires hardware support
- ⋆ performance...

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Drawbacks:

- ⋆ prototype is 32-bit only
- ⋆ performance?

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Drawbacks:

- ⋆ applications must handle capabilities (e.g. on RPC)
- ⋆ no fast rights amplification
- ⋆ performance!

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Drawbacks: ⋆ special hardware!

MUNGI [HEV+98] (UNSW, 1994–now)

- “pure” SASOS (no message-passing IPC)
- standard 64-bit hardware
- discretionary and mandatory access control
- user-level device drivers and system extensions
- POSIX emulation
- fastest SASOS to date

SASOS Issues

- Protection model
- System extensibility
- POSIX compatibility
- Resource Management
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Discussed in context of Mungi

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  - ➜ *user-oriented* mechanism
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  - ➜ *system-oriented* mechanism
  - ➜ system-wide *security policy* limits data flow
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Mungi has both

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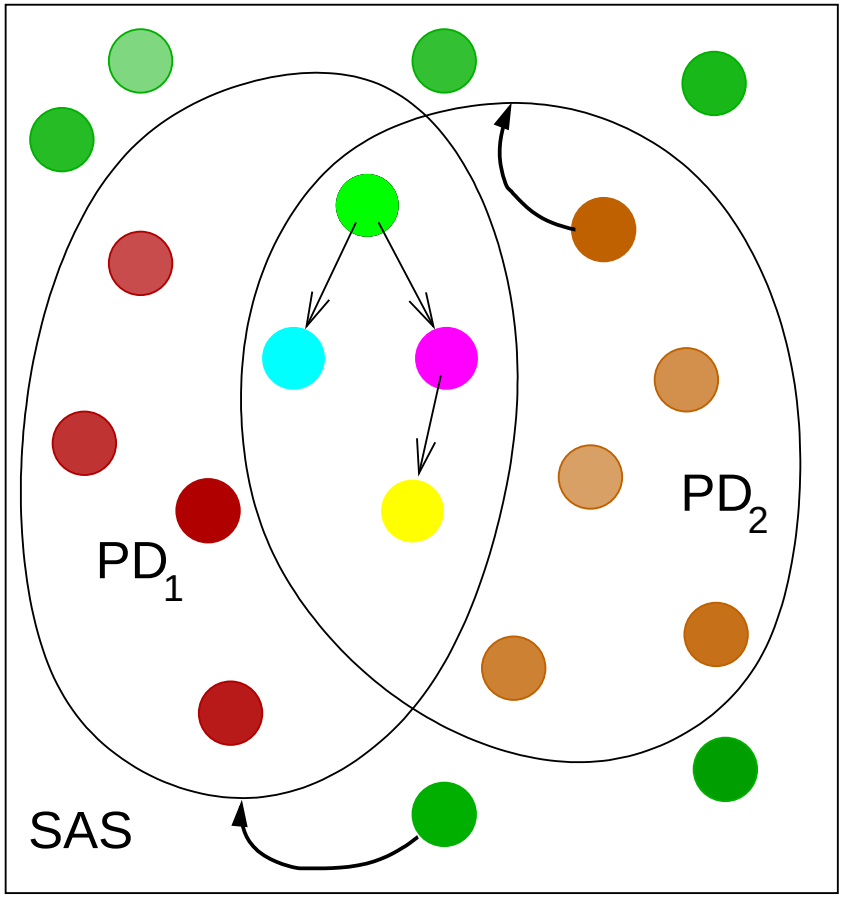
- A protection domain is defined as a set of *capabilities*
- Capabilities and protection domains are user-level objects



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- Threads execute inside a *protection domain* (PD)
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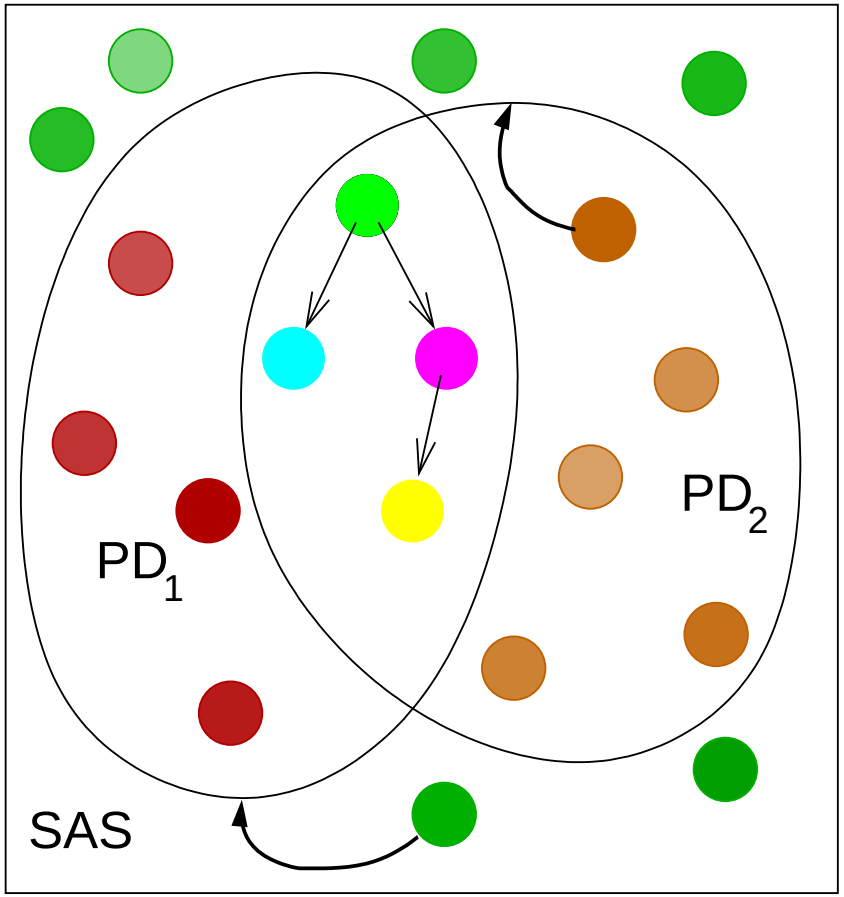
- Capabilities and protection domains are user-level objects
- Thread may or may not have control over its PD

  ➜ supports user-controlled confinement



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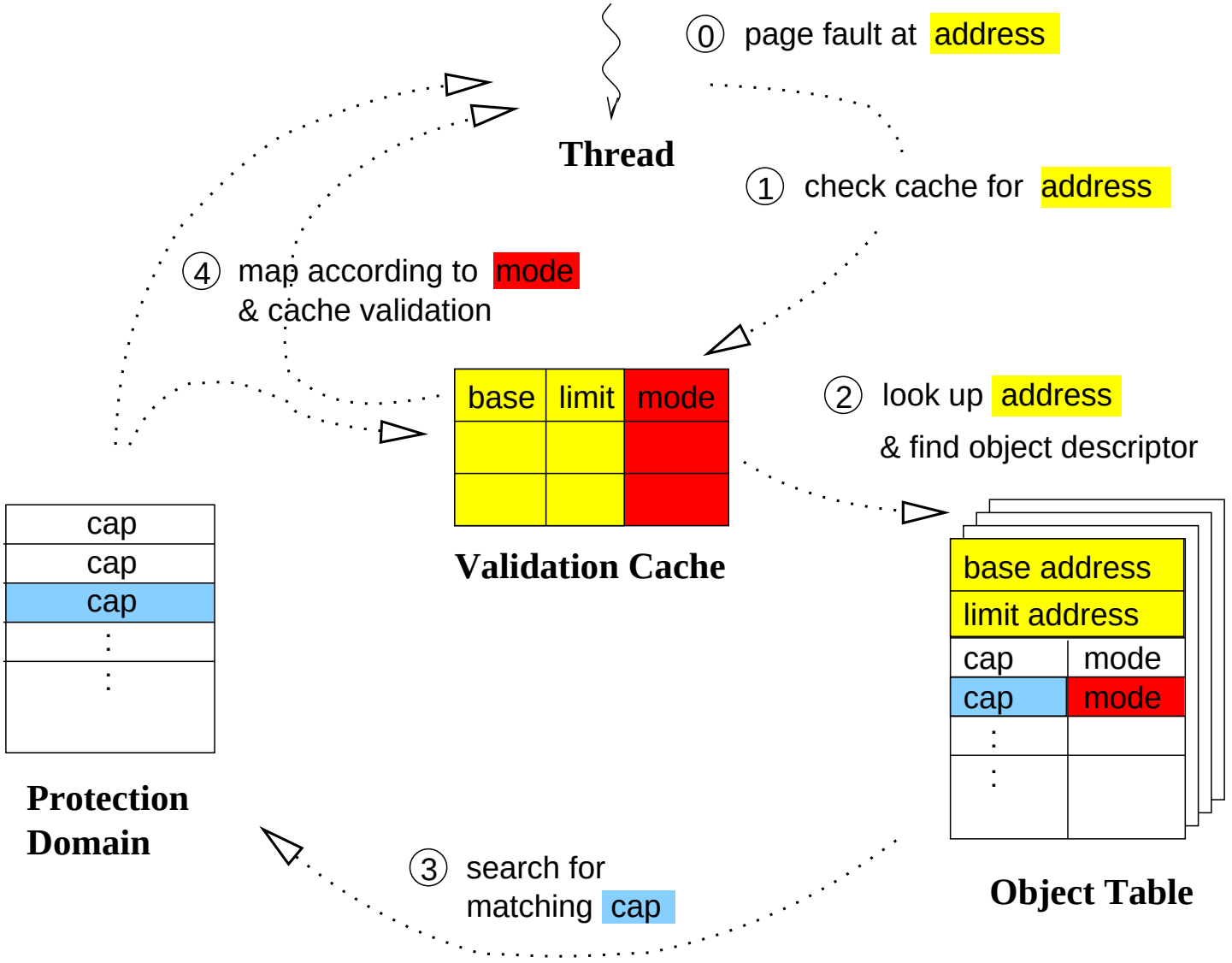
- Caps confer sets of rights, combination of:
  - ➜ `read`, `write`, `execute`, `delete`, `enquire`, `PDX`

ACCESS VALIDATION:



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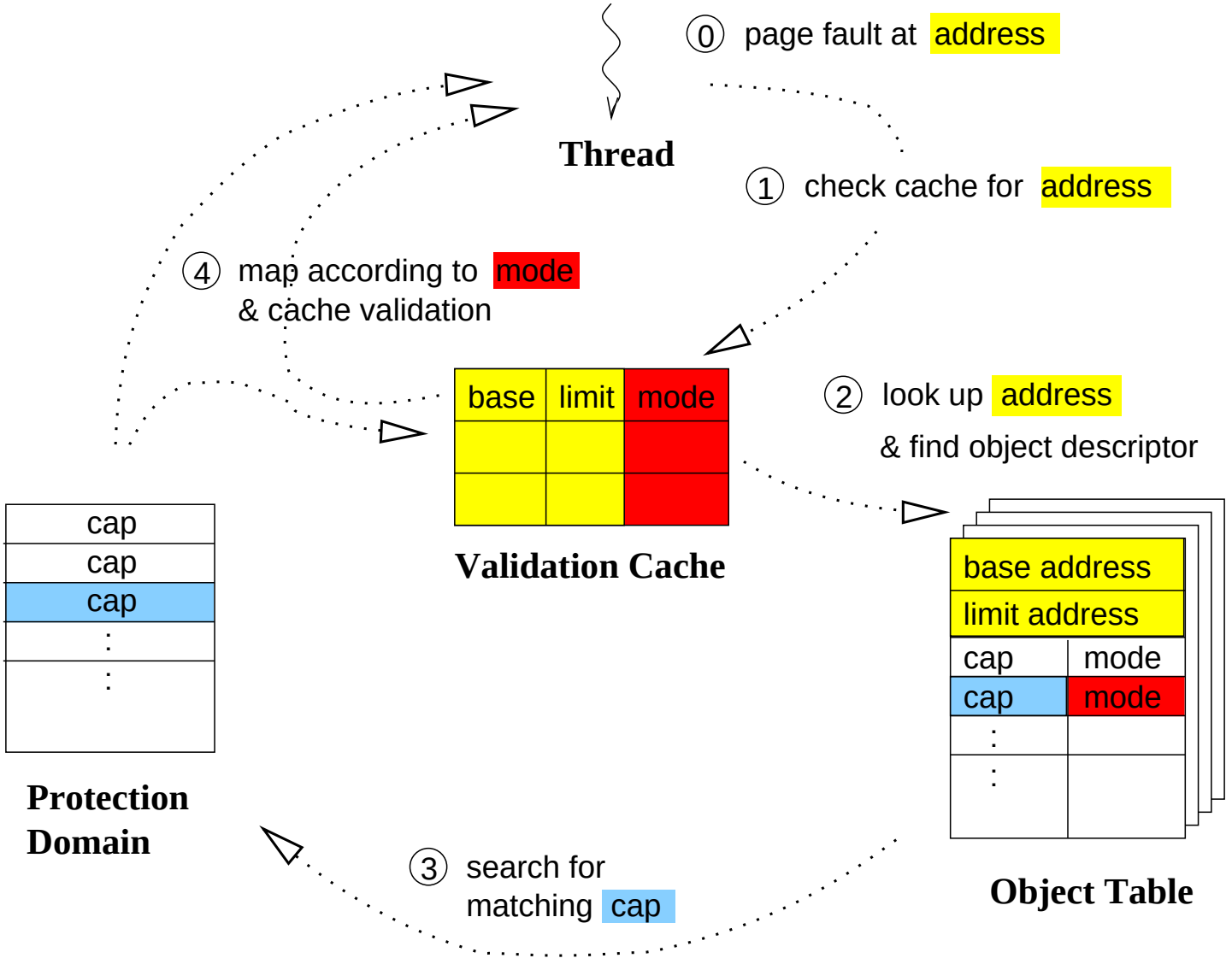

Note: All capability presentation is *implicit*

THREADS AND PROTECTION DOMAINS

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- New APD is instantiated from a template
  - ➜ called the *protection domain object* (PDO)
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  - ➜ PDO creation requires special privileges
- Thread can also change APD temporarily
  - ➜ called *protection-domain extension*, PDX
  - ➜ requires PDX cap
  - ➜ serves as protected-procedure call mechanism

Protected Procedure Calls

- Object can have (PDX) type:
  - ➜ has *PDX capabilities*,
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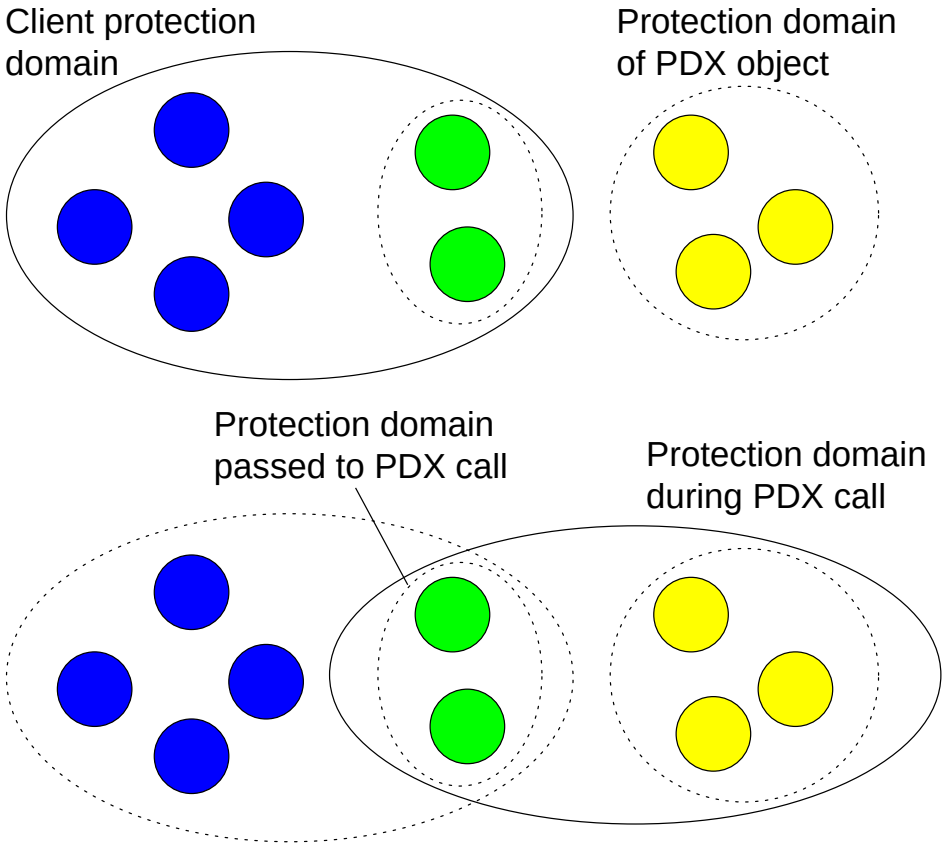
- Allows secure invocation of an object in a PD different from caller's
- *Discretionary* access control validates entry points and invocation right



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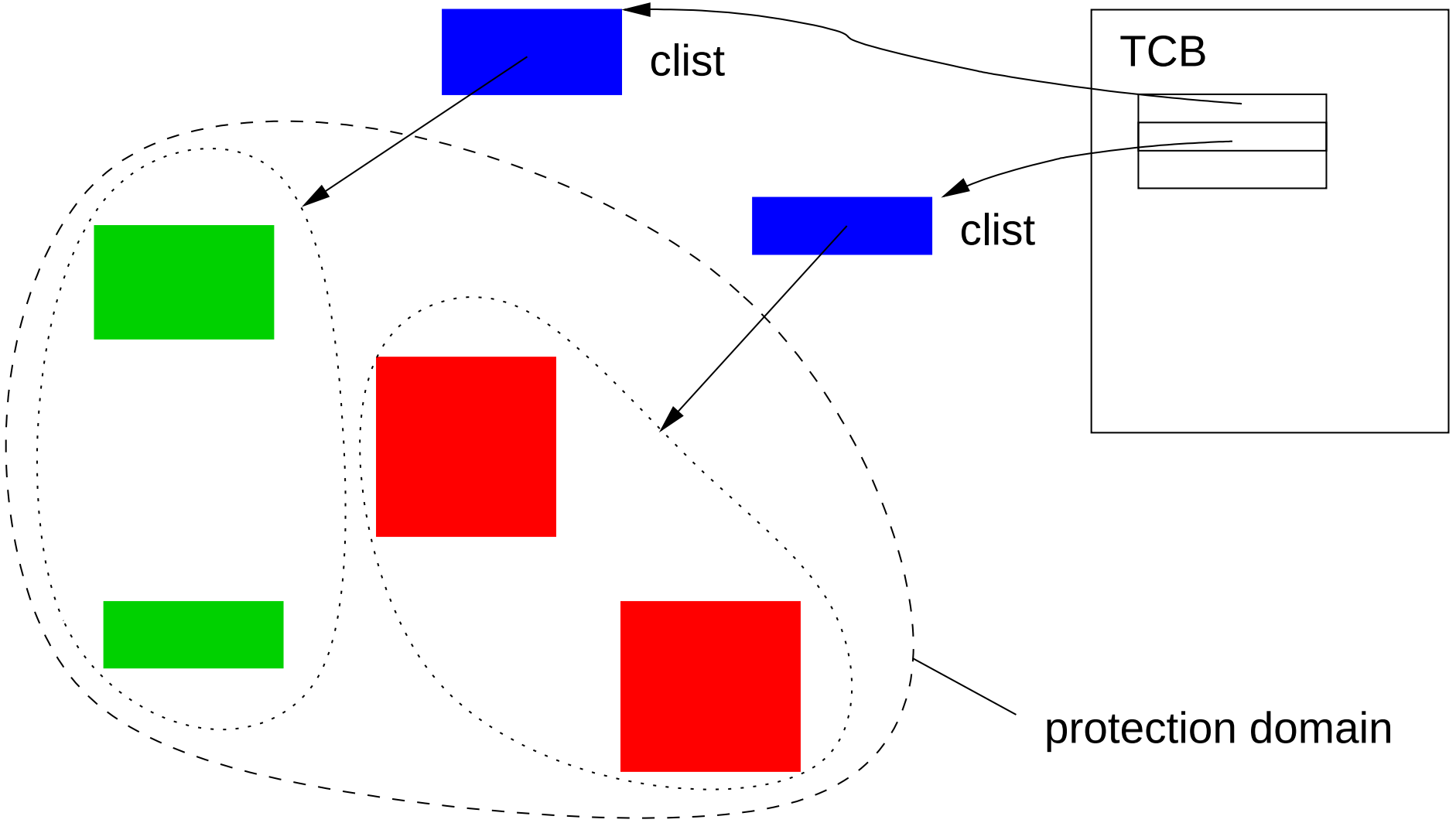
- Such a thread is *confined*.

Discretionary Confinement in Mungi



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- System-wide security policy is a relation on types and domains

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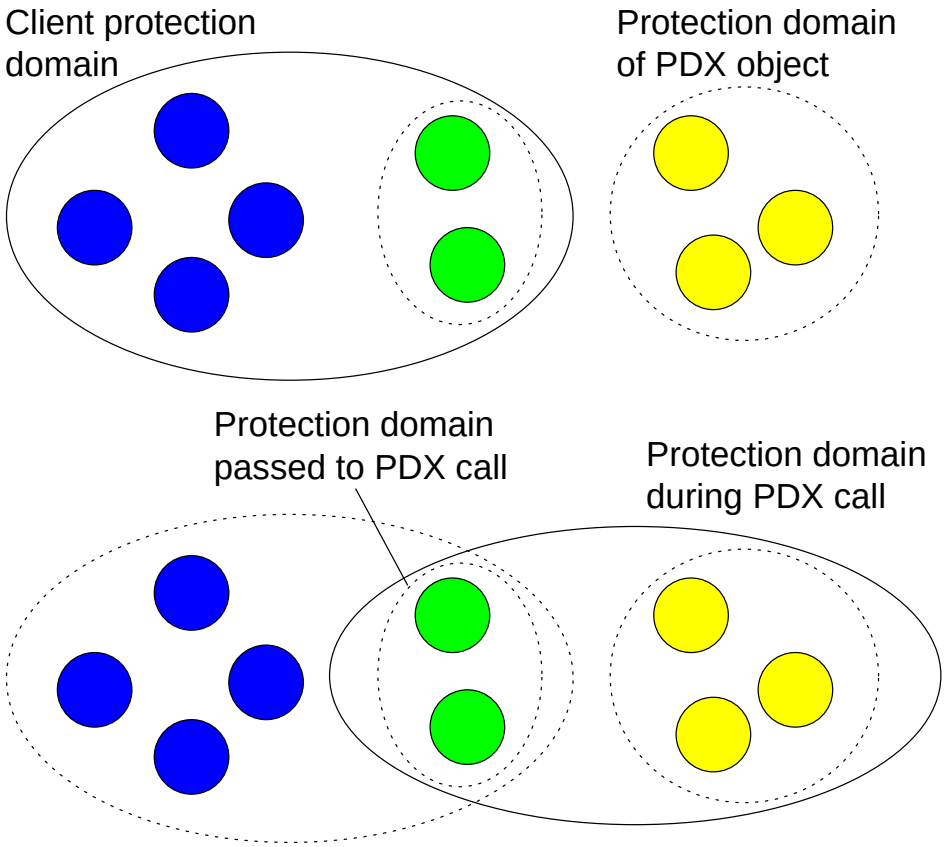
- Policy object consists of a number of (mostly simple) validation functions
  - ➜ invoked via PDX $\Rightarrow$ also subject to MAC!
  - ➜ MAC validations are cached in separate validation cache

PDX AGAIN...

- ➜ *discretionary* access control validates entry points and invocation right
- ➜ *mandatory* access control validates right to use target PD
- ➜ *discretionary* and *mandatory* access control validate data access



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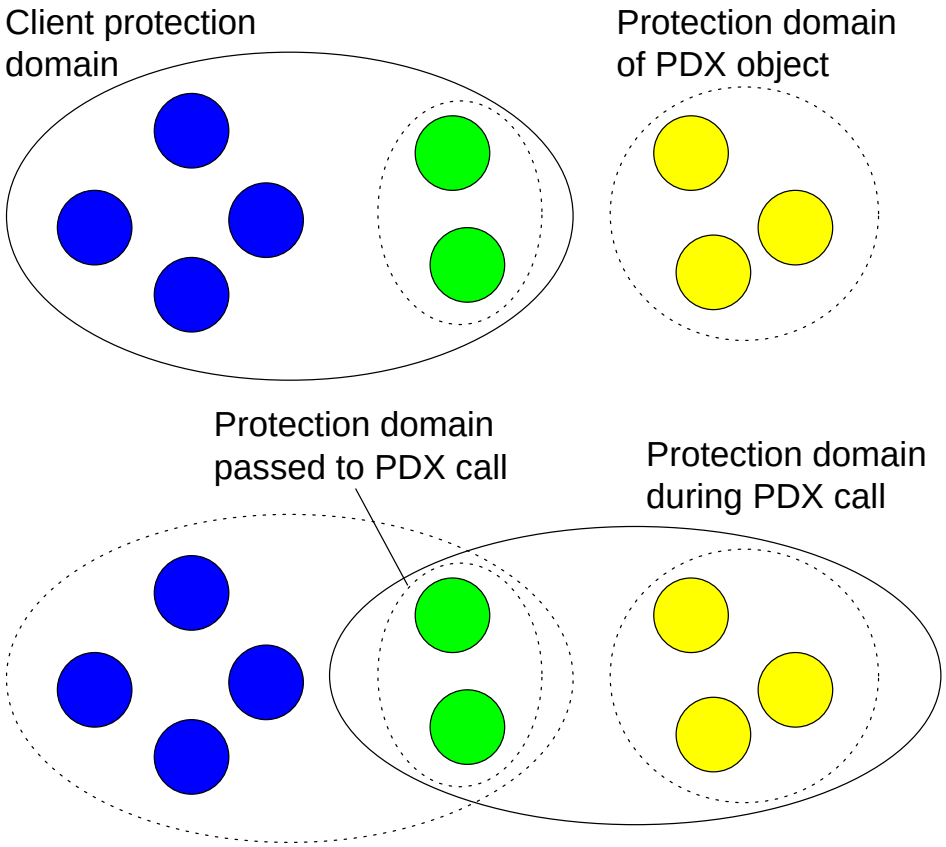
- ➜ *discretionary* and *mandatory* access control validate data access



- Can use this as the basis for secure system extensions!
  - ➜ Component model based on PDX for extending system

OS Extensibility

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  - ➜ Run as part of the kernel $\Rightarrow$ no protection.
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- User-level servers (Mach, Windows-NT):
  - ➜ based on message-based communication with servers,
  - ➜ performance problems ⇒ migrate extensions into kernel.
  - ➜ newer systems try to do better (e.g. SawMill)

EXISTING APPROACHES TO OS EXTENSIBILITY (CONT'D)

- Safe kernel extensions by *trusted code* (e.g. SPIN [BSP+95]):
  - ➜ extensions must be programmed in *type-safe* language (Modula-3),
  - ➜ restrictive programming model,
  - ➜ large trusted computing base,
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- Safety by *sandboxing* kernel extensions (e.g. Vino [SESS96]):
  - ➜ poor performance.

WHAT'S WRONG?

- Kernel extensions create huge *security problems*.
  - ➜ Kernel code is inherently unrestricted.
  - ➜ Imposition of restrictions results in *cost* and *complexity*.
- User-level extensions can be secure but:
  - ➜ have potential *performance problems*, and
  - ➜ need to be supported by an appropriate *framework*.

WHAT'S NEEDED?

User-level extensibility can be made to work if [EH01b]:

- Performance can be ensured.
  - ➜ Requires fast inter-process communication.
  - ➜ Has been demonstrated (L4, Pebble, Mungi).

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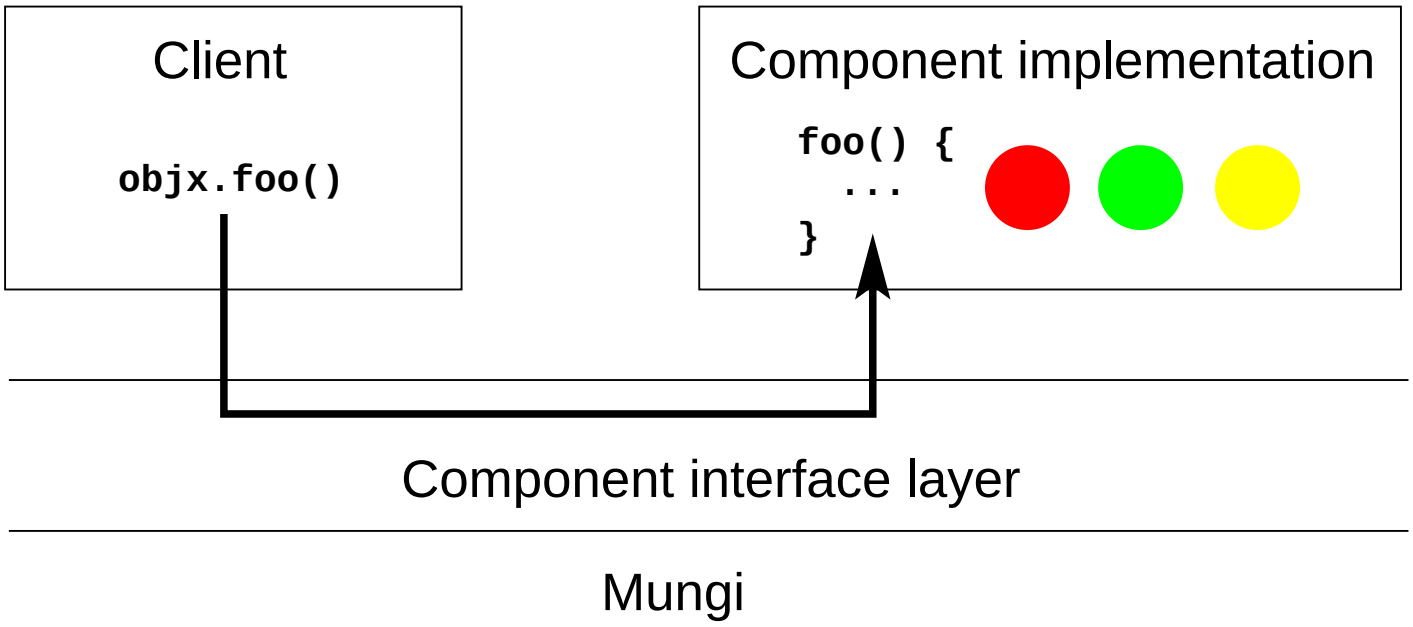
  - ➜ Will work if OS protection is *strong and flexible* enough.
- A framework for extensions is provided which supports:
  - ➜ transparent invocation of extended services,
  - ➜ low overhead extension and customisation of extensions,
  - ➜ software technology to minimise complexity.

Mungi Component Model



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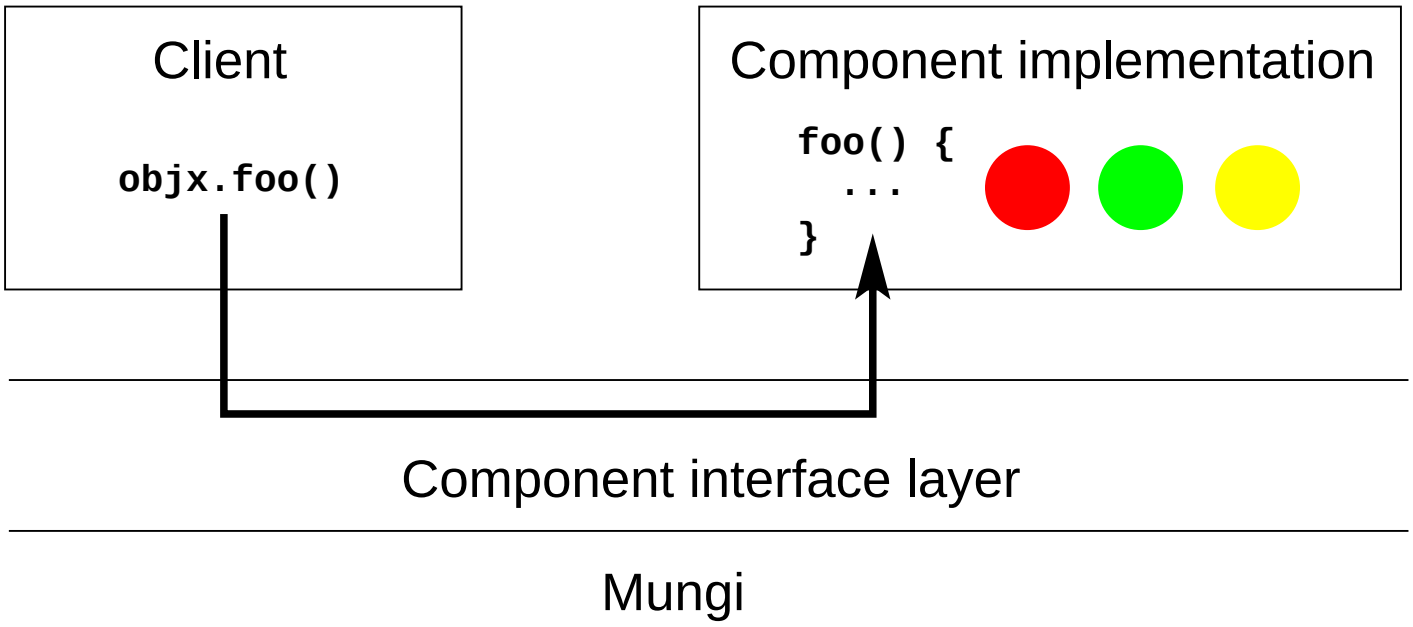
Mungi Component Model



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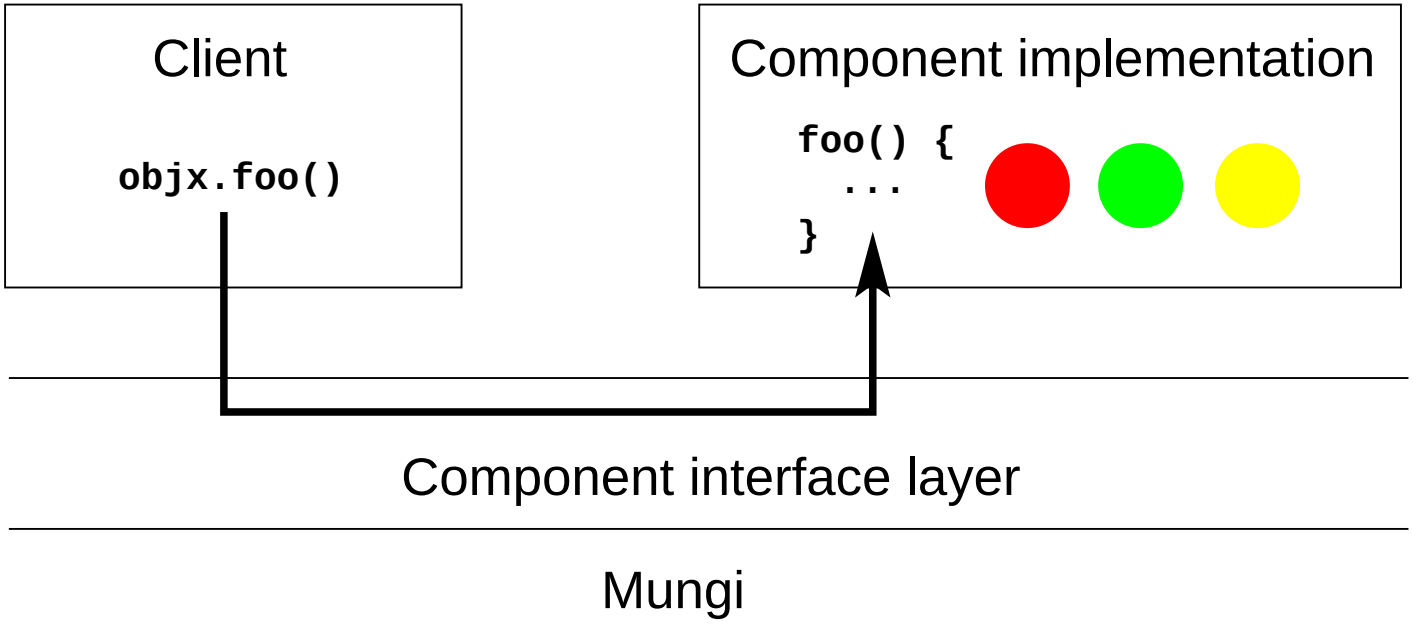

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- PDX is used for invocation
- Component data is created *inside* the component PD
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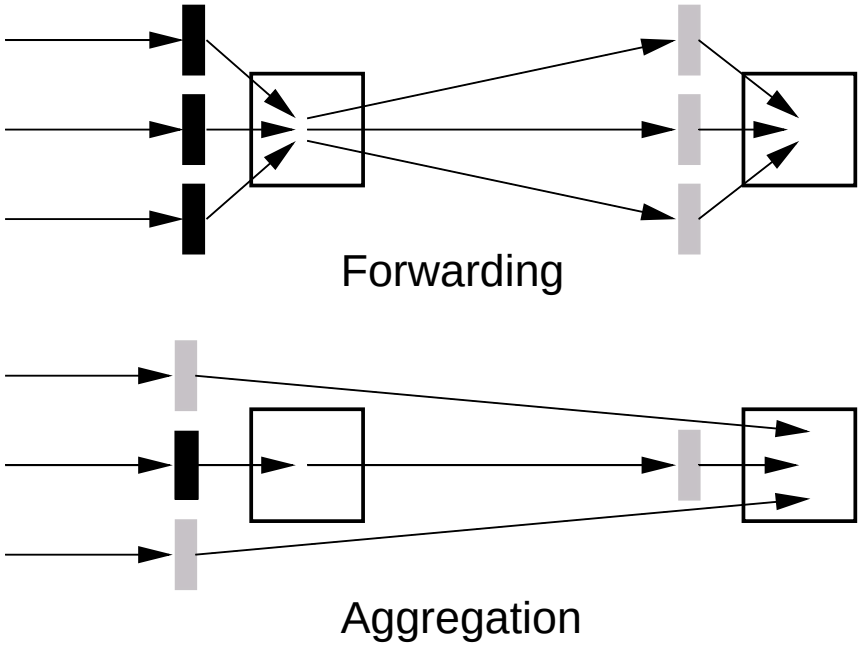
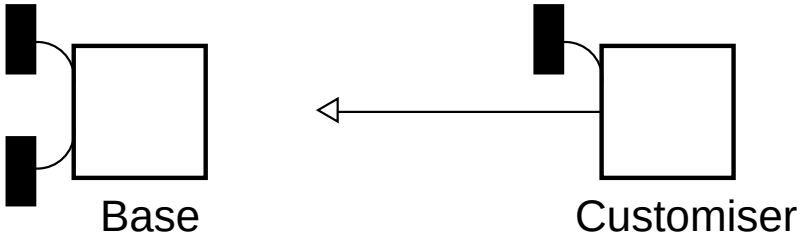
- Single address space ⇒ *no need to marshal arguments!*

EXTENDING EXTENSIONS

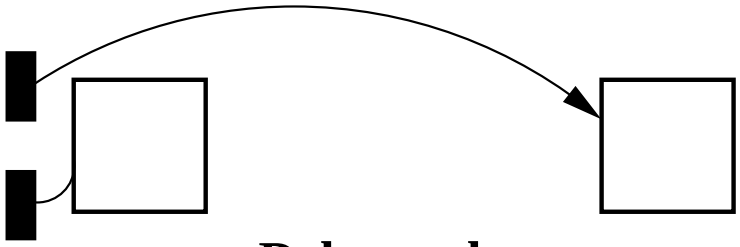


- Components export *interfaces*.
- Component instances can invoke interfaces of other instances (and thus extend them): *forwarding*.
- *Aggregation* allows direct invocation of extended interface.

CUSTOMISATION



Request Delegation



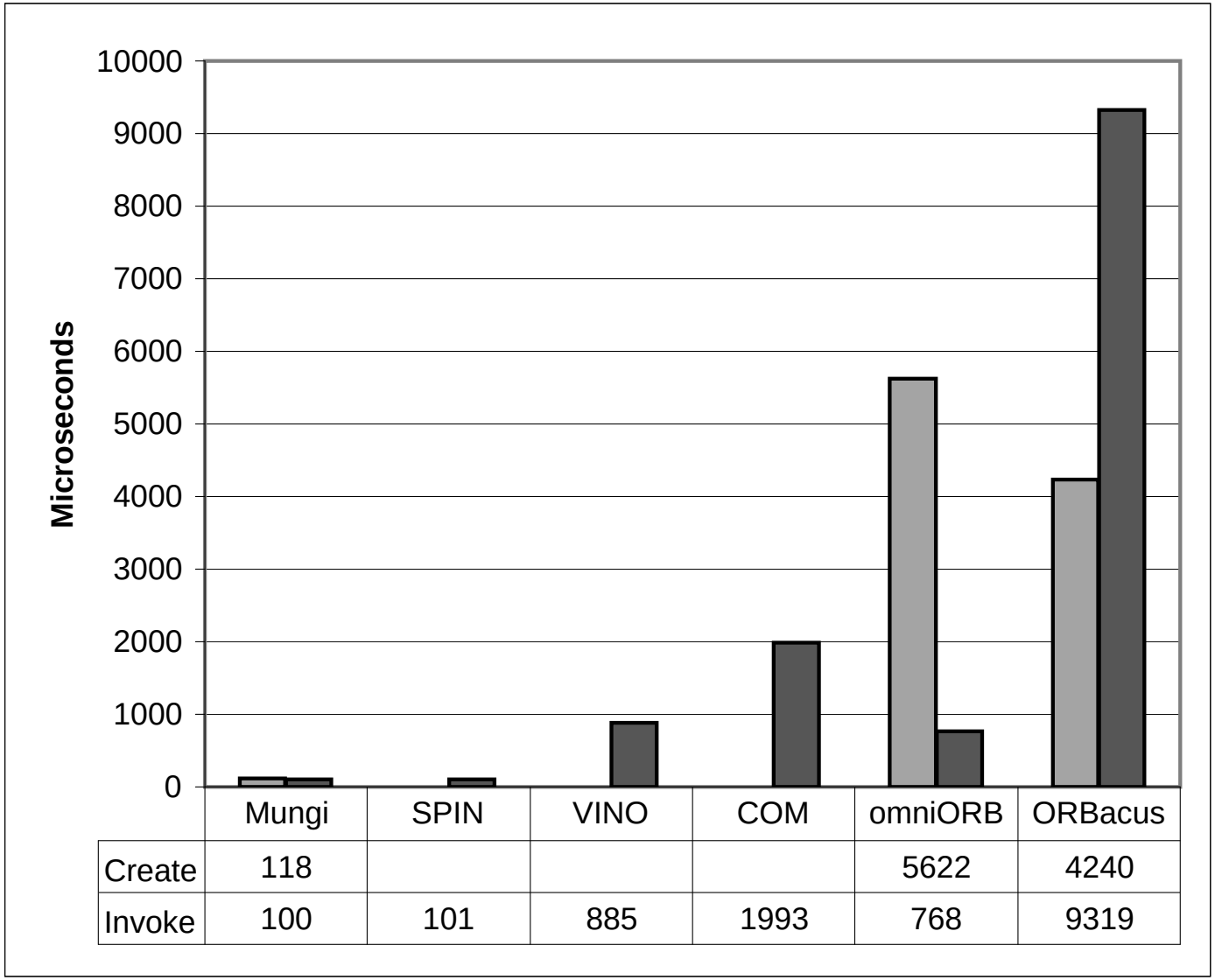
Delegated

- ➜ *Delegation* is a dynamic form of aggregation that allows an invocation of a base component to be transparently handled by another component.
- ➜ Avoids the semantic nightmares of *virtual inheritance*.

OVERHEAD OF MANDATORY ACCESS CONTROL

Benchmark	no MAC ms	with MAC ms	O/H %
OO1	187.8	187.8	0.0
Jigsaw$_{56\times56}$	374	375	0.3
Andrew	672	674	0.3

EXTENSION SYSTEM PERFORMANCE: MICROBENCHMARKS



	Mungi	SPIN	VINO	COM	omniORB	ORBacus
Create	118				5622	4240
Invoke	100	101	885	1993	768	9319

EXTENSION SYSTEM PERFORMANCE: MACROBENCHMARKS

Environment	Time
Linux (RAM disk)	283 ms
Mungi (statically linked)	146 ms
Mungi (extension)	247 ms

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