Operating Systems Research at UNSW and NICTA

and

Opportunities for Students

COMP9242 2004/S2 Week 14

OVERVIEW

- What is NICTA?
- Embedded systems research agenda
- Present projects
- Opportunities

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- Locations:
  - ⋆ Sydney (UNSW campus and ATP technology park)
  - ⋆ Canberra
  - ⋆ Melbourne (University of Melbourne Campus)
  - ⋆ Brisbane (in progress)

NICTA's Four Pillars

- Research
- Education
- Linkages
- Commercialisation

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- Linkages
  - ➜ collaborate with top research institutions around the world
- Commercialisation
  - ➜ turn research into products
  - ➜ focus on
    - ➜ local small and medium-sized enterprises (SMEs)
    - ➜ multinational corporations (MNCs)

NICTA Structure

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- *International Science Advisory Group*
  - ➜ Richard Newton (UCB), Shankar Sastry (UCB), Raj Reddy (CMU), Rodney Brooks (MIT), Jeff Ullman (Stanford), Gunnar Bjurel (SIKS), Gilles Kahn (INRIA), Ya-Qin. Zhang (Microsoft), ...

EMBEDDED, REAL-TIME AND OPERATING SYSTEMS (ERTOS) PROGRAM

- One of presently 16 Research Programs in NICTA
  - ➜ 8 FTE PhD-qualified researchers (1 vacant)
  - ➜ 11 FTE research engineers / research assistants (2 PhDs)
  - ➜ 20 PhD students (10 core OS topics)
- Competencies in
  - ➜ operating systems, microkernels
  - ➜ networking
  - ➜ real-time systems
  - ➜ reconfigurable computing
  - ➜ programming languages and compiler front-ends

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  - ⋆ innovation concentrated in SMEs
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  - ⋆ main focus is on software
  - ⋆ reconfigurable hardware will be increasingly important
    - ➜ prototyping
    - ➜ small series
    - ➜ flexibility

NICTA Priority Challenge:
Trusted Wireless Networks

To enable greater confidence, freedom, and capability through improved efficiency, reliability, and security of all wireless environments.

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NICTA PRIORITY CHALLENGE: TRUSTED WIRELESS NETWORKS

To enable greater confidence, freedom, and capability through improved efficiency, reliability, and security of all wireless environments.

- Strongly based on embedded systems technology
- Issues relevant to ERTOS:
  - ⋆ efficiency
  - ⋆ reliability
  - ⋆ security
  - ⋆ cost

ERTOS VISION

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ERTOS research is to be driven by applications

- to identify common challenges
- to provide generic systems software

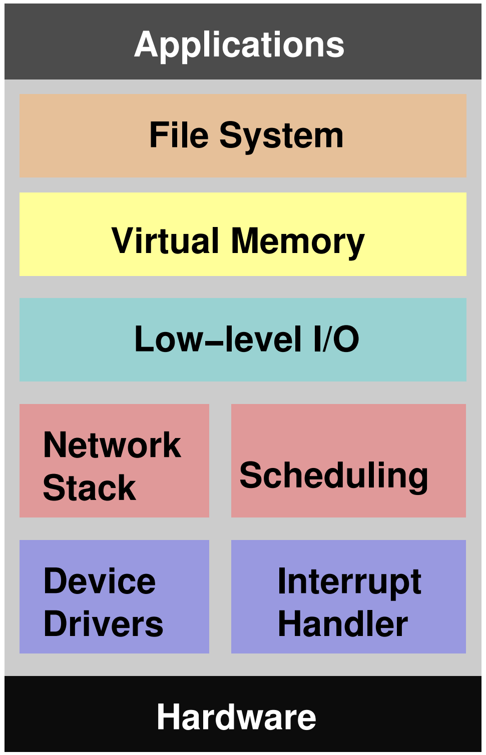
EMBEDDED SYSTEM

Computer system that is part of a larger system

General-Purpose vs. Embedded

Traditional view:

general-purpose system



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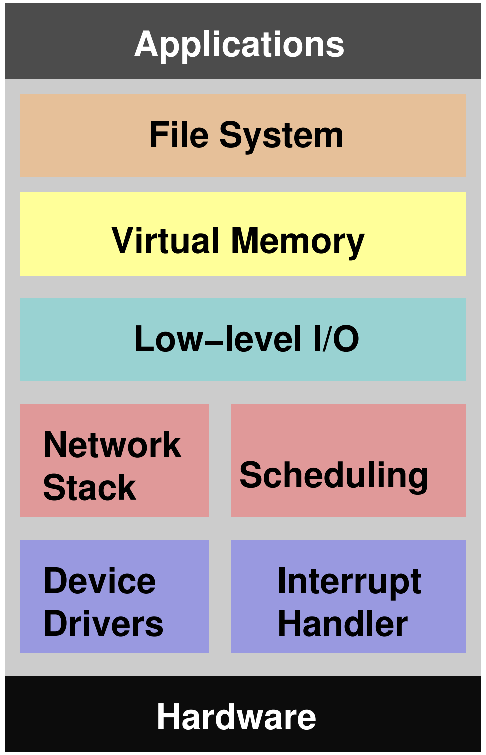

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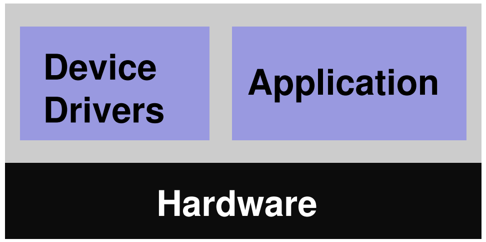

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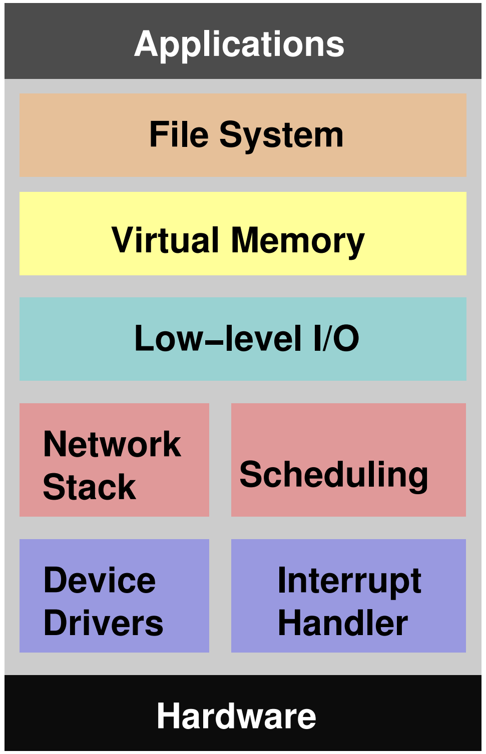

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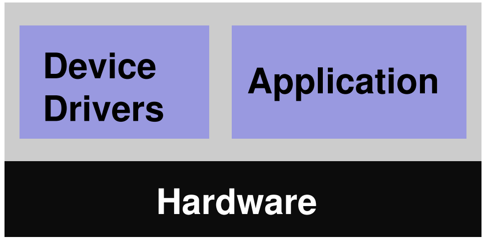

- ➜ minimal
- ➜ no OS at all or small "real-time executive"
- ➜ no protection

Security Challenges

- Growing functionality

- Wireless connectivity

- Downloaded contents (entertainment)

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SECURITY CHALLENGES

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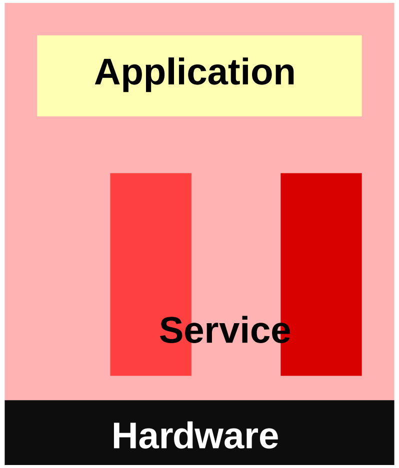
- Wireless connectivity
  - ➜ subject to attacks from outside (crackers)
- Downloaded contents (entertainment)
  - ➜ subject to attacks from inside (viruses, worms)
- Increasing dependence on embedded systems
  - ➜ increased exposure to embedded-systems security weaknesses

PRESENT APPROACHES 1: REAL-TIME EXECUTIVES



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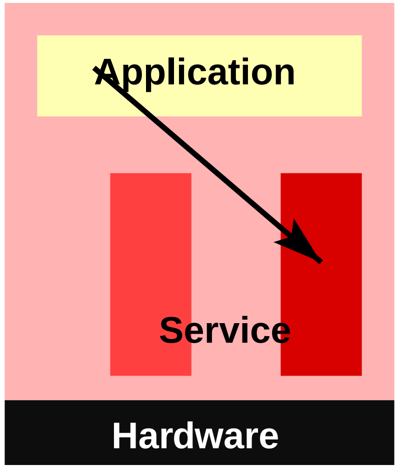

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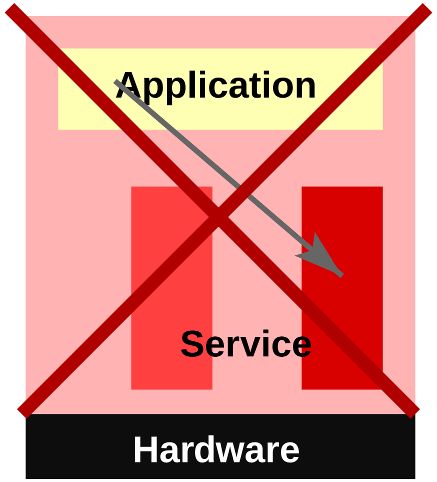

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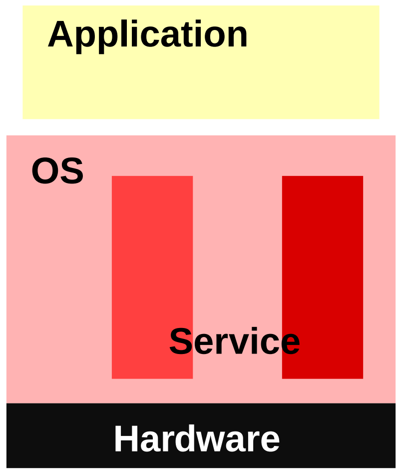
  - ➜ every small bug/failure is fatal
  - ➜ no defence against viruses, limited defence against crackers

PRESENT APPROACHES 2: LINUX, WINDOWS EMBEDDED, ...



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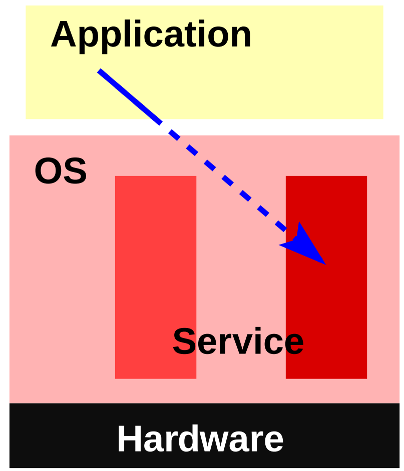

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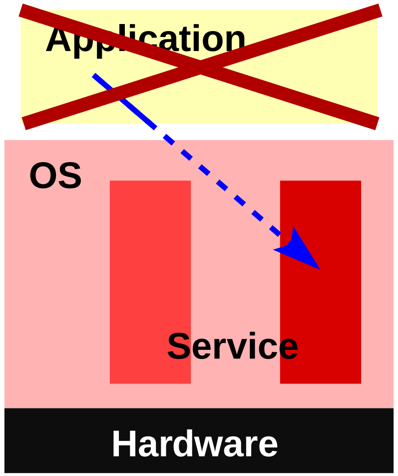

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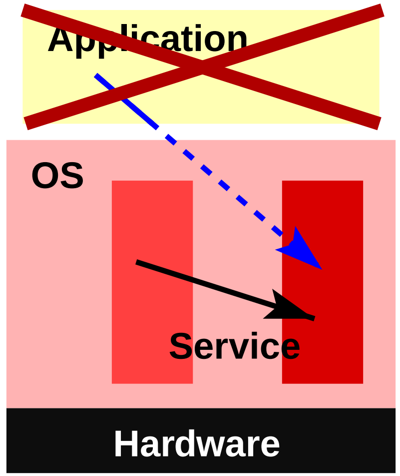

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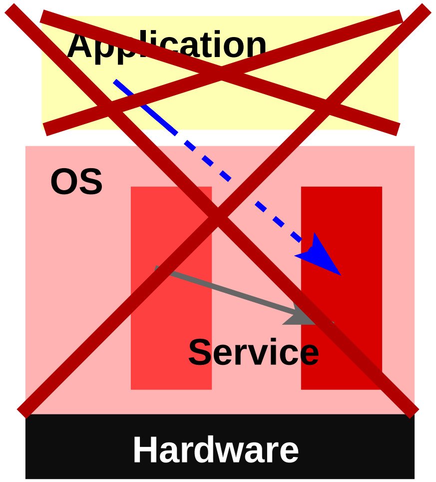

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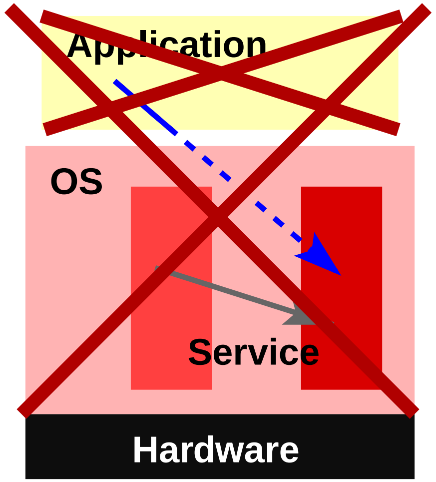

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  - ➜ operating system protected from application misbehaviour
  - ➜ excessive code base for small embedded system
  - ➜ too much code on which security of system is dependent
- Dubious or non-existent real-time capabilities
  - ➜ unsuitable for hard real-time systems

Embedded Systems Requirements:

Reliability, trustworthiness, security

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- Why minimal TCB?
  - ✓ minimise exposure to bugs/faults
  - ✓ minimise exposure to attacks (internal and external)
  - ✓ support poorly-scaling verification methods

Trusted Computing Base

What does the TCB contain?

TRUSTED COMPUTING BASE

WHAT DOES THE TCB CONTAIN?

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- *Everything* on MPU-less processors
  - ✗ no memory-protection hardware $\Rightarrow$ no memory protection

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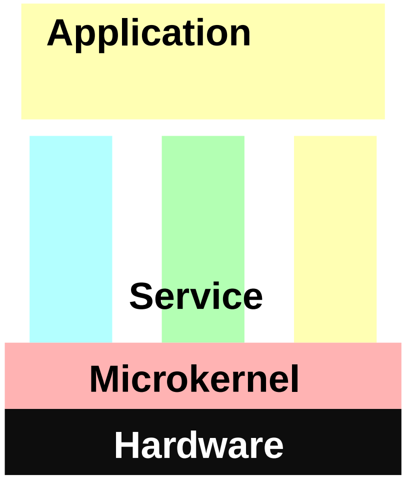
- *Minimal TCB required* $\Rightarrow$ *microkernel required!*

NICTA APPROACH: MICROKERNEL



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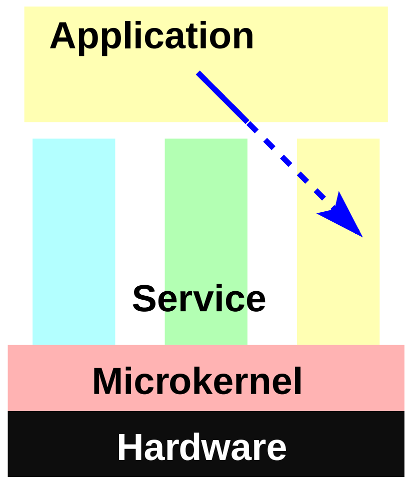

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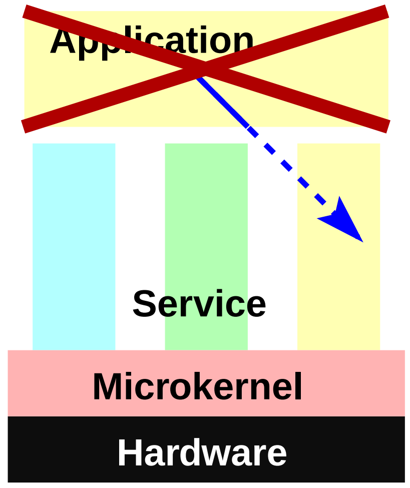

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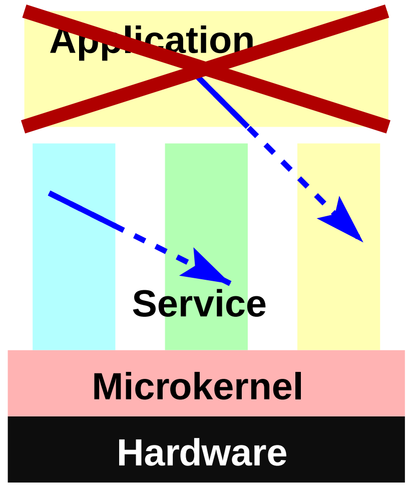

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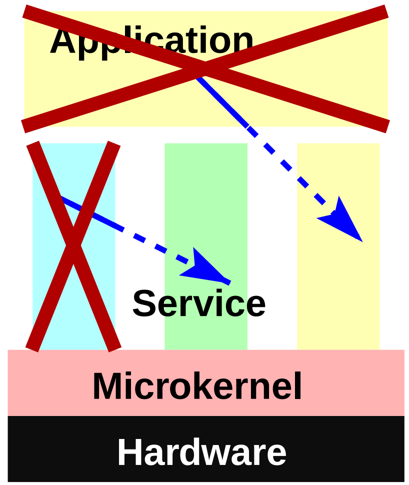

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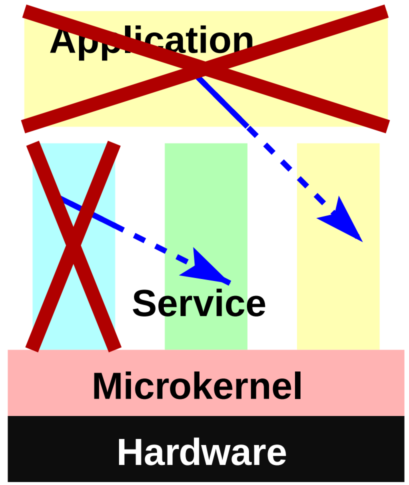

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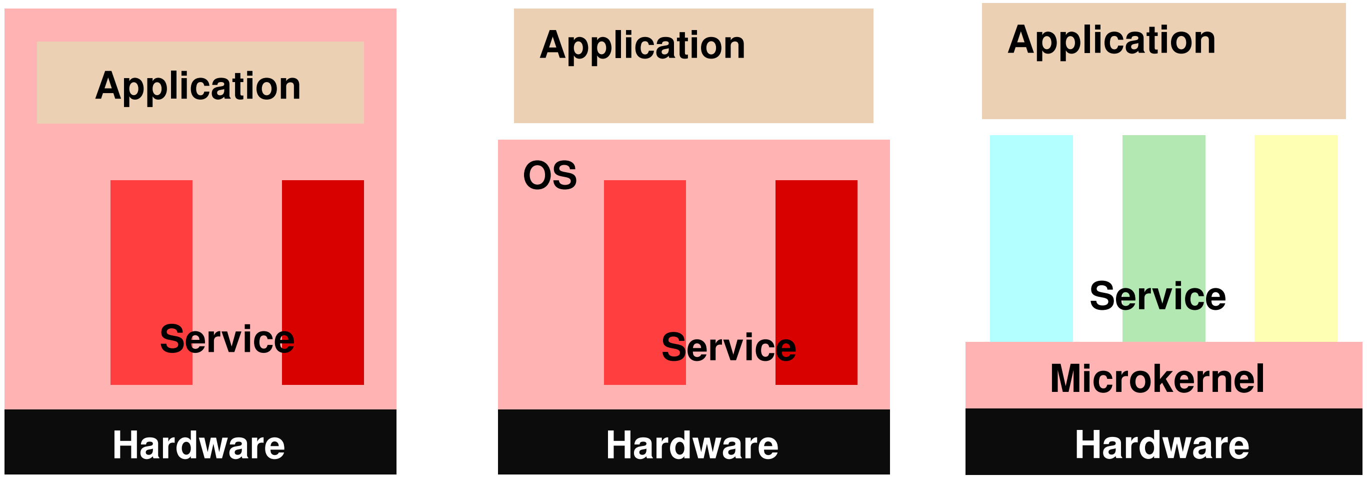
- What's the difference?

TRUSTED COMPUTING BASE



System:	traditional embedded	Linux/ Windows	Microkernel-based
TCB:	**all** code	100,000's loc	10,000's loc

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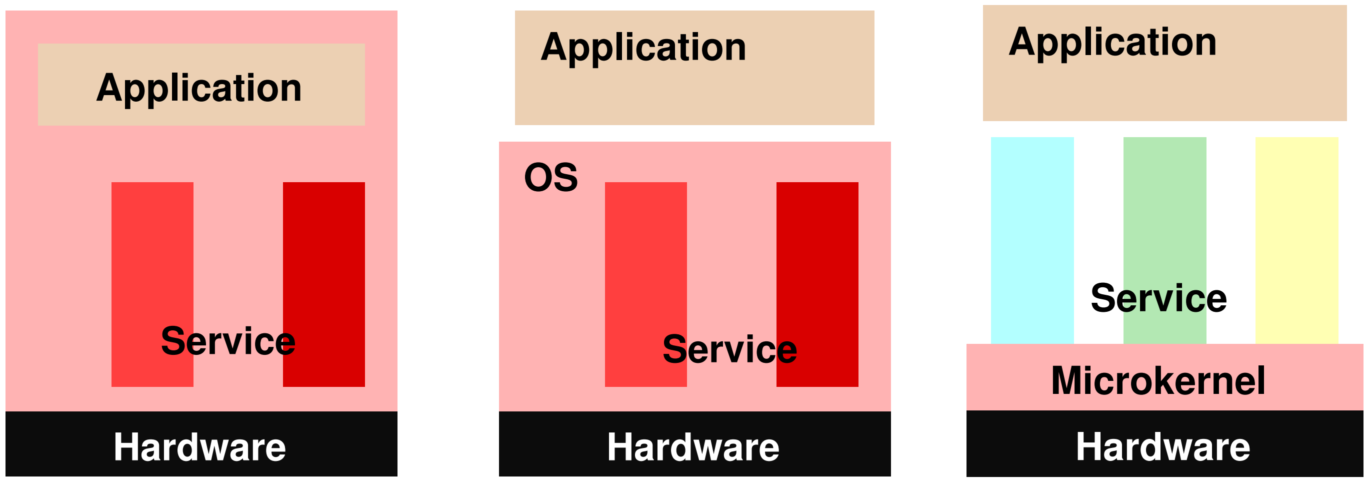

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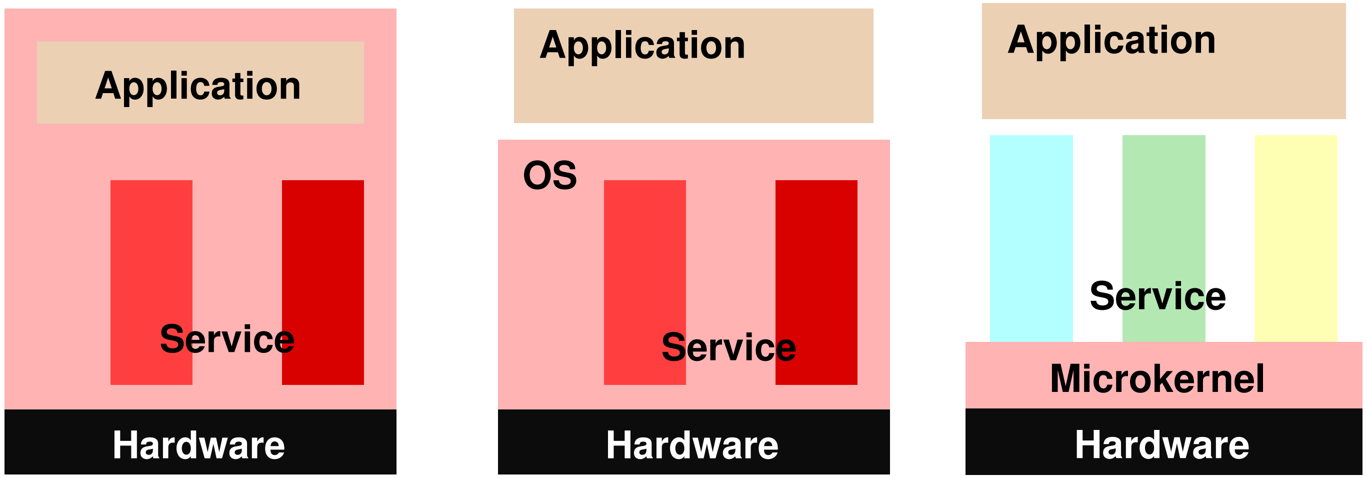

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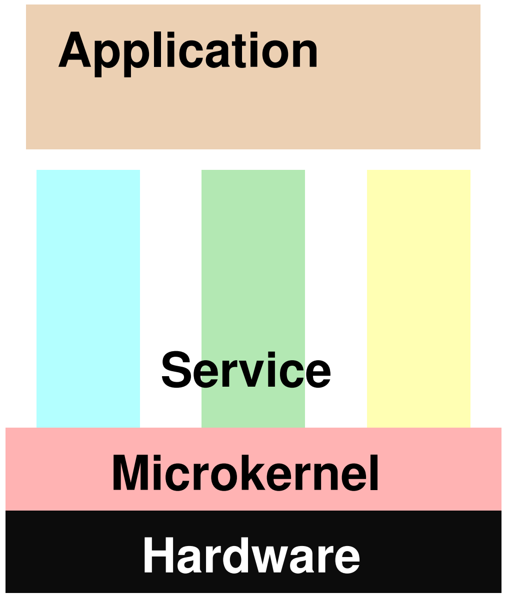
Challenge: Can we *guarantee* the trustworthiness of the TCB?

MICROKERNEL BENEFITS

- Fault isolation
  - ☑ other components protected from fault
- Hot swapping / hot upgrade
  - ☑ can replace servers on running system
- Software engineering techniques
  - ☑ componentised system
- Enforcement of security policies
  - ☑ kernel controls communication even between system services
- Resource management for system services
  - ☑ OS servers are like normal user code
- Formal verification
  - ☑ hardware-enforced isolation reduces complexity



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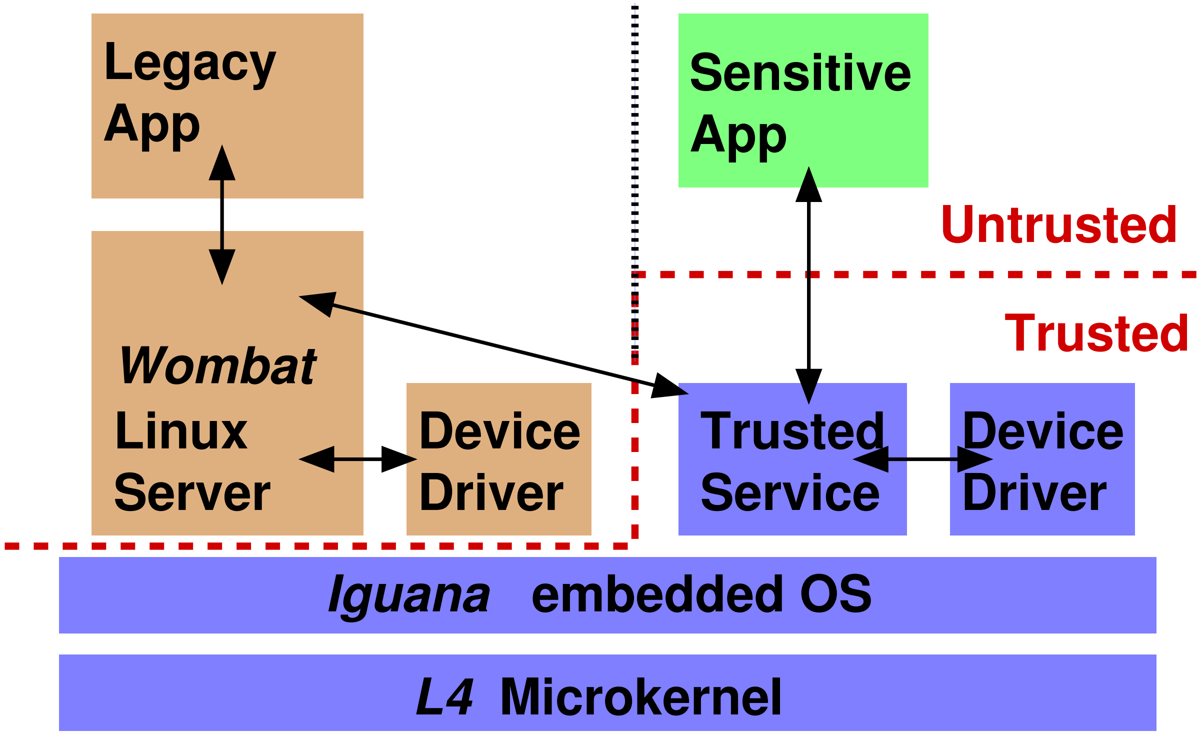

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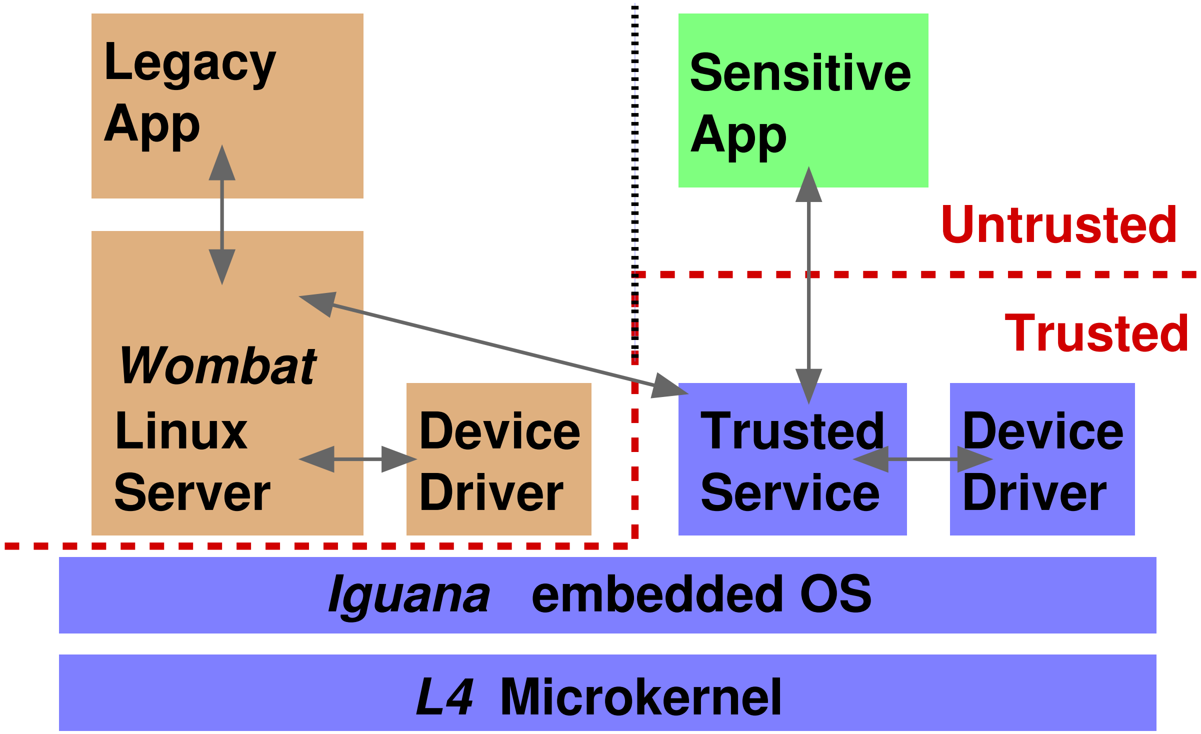

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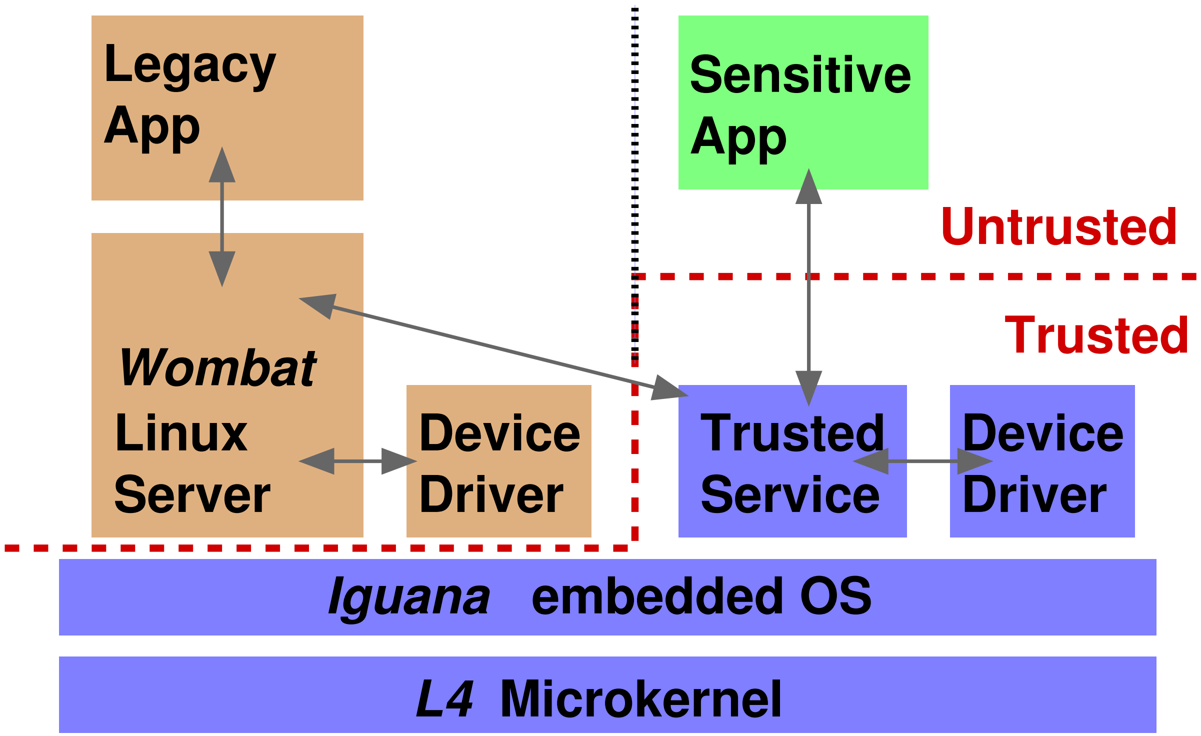

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  - ➜ full binary compatibility with native Linux
- Compromised legacy system cannot interfere with trusted part

L4: NICTA L4-EMBEDDED API

SIMPLER/SMALLER IMPLEMENTATION

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  - ➜ physically-addressed TCBs $\Leftarrow$ *honours thesis*
  - ➜ single kernel stack per CPU $\Leftarrow$ *honours project*

IGUANA: OS PERSONALITY FOR EMBEDDED SYSTEMS

- Remember, L4 is (almost) a “strict” microkernel:
  - ➜ does not provide any services
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  ... based on some system-wide policies
- Iguana provides these (or at least more tools for providing them)
  - ➜ designed for use in embedded systems
  - ➜ designed to minimise trusted computing base

What does Iguana Provide?

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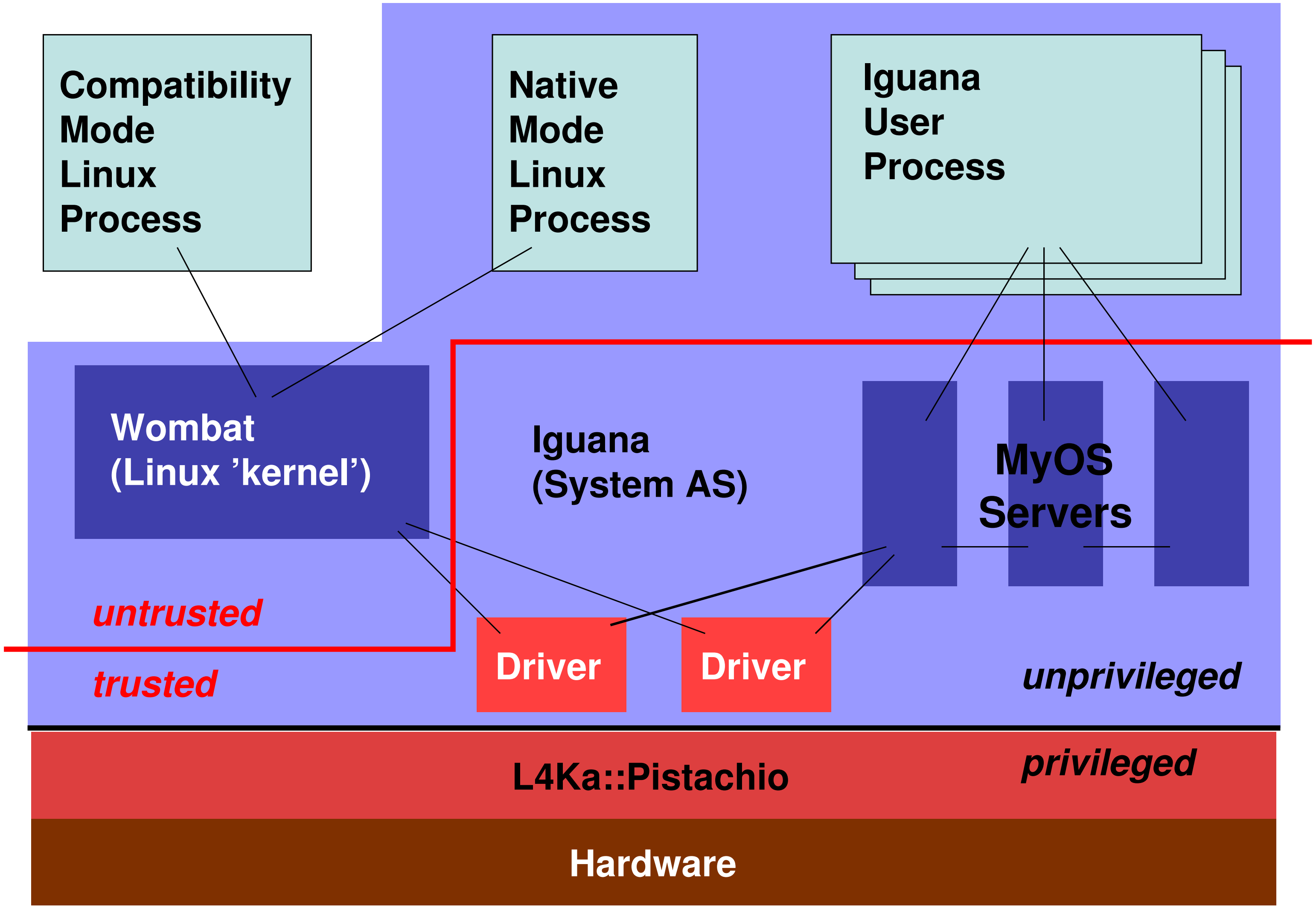
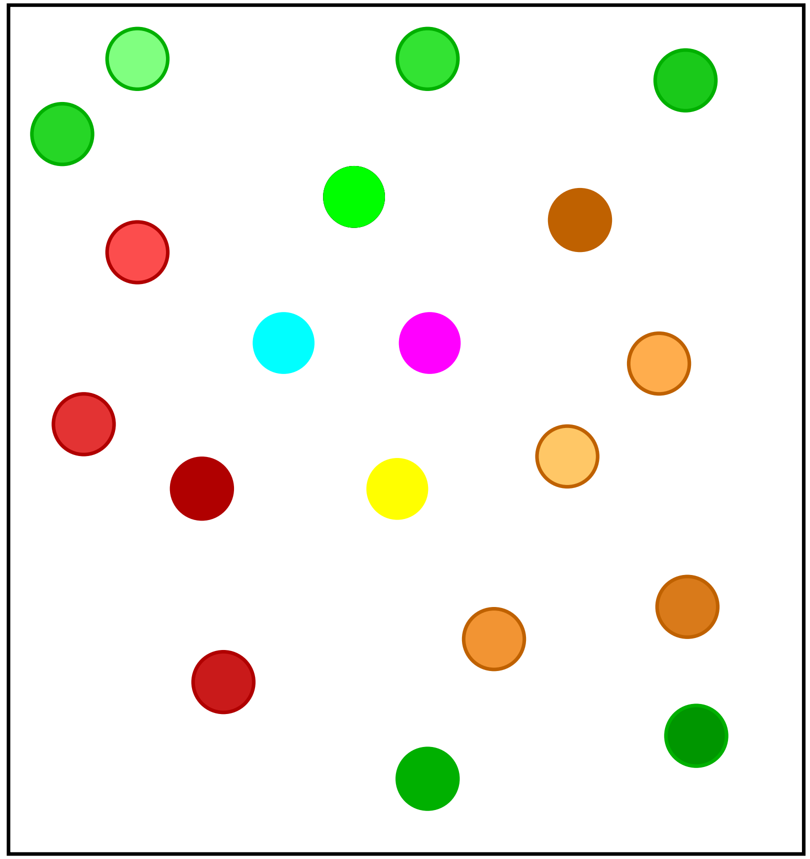
- ⋆ Thread management

SAMPLE IGUANA SYSTEM



Iguana: Basic Approach

- Basic idea: single address space (SAS)



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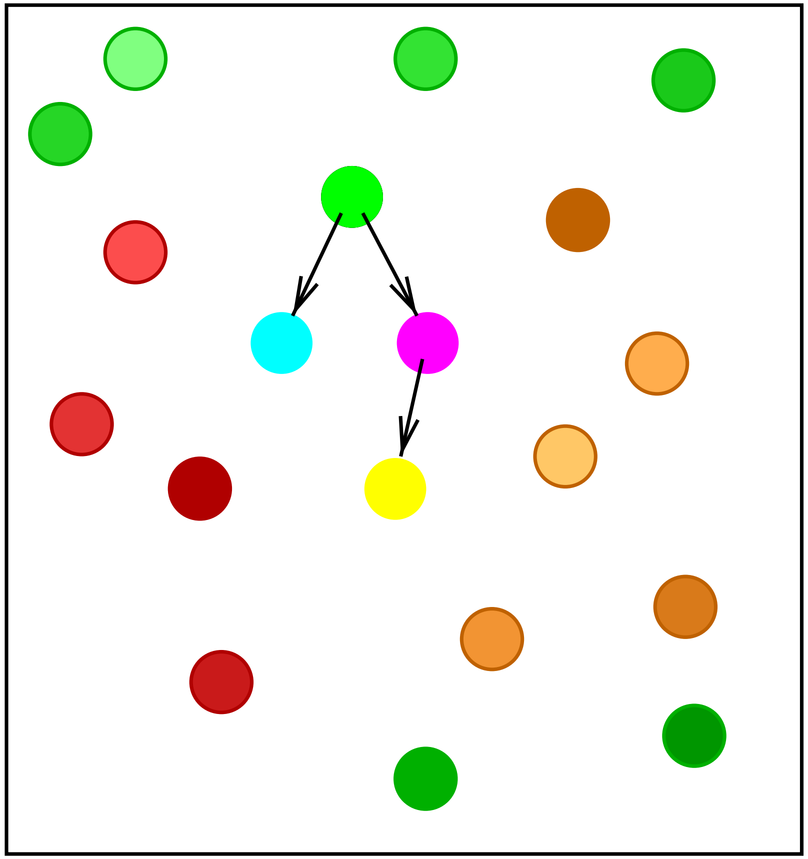

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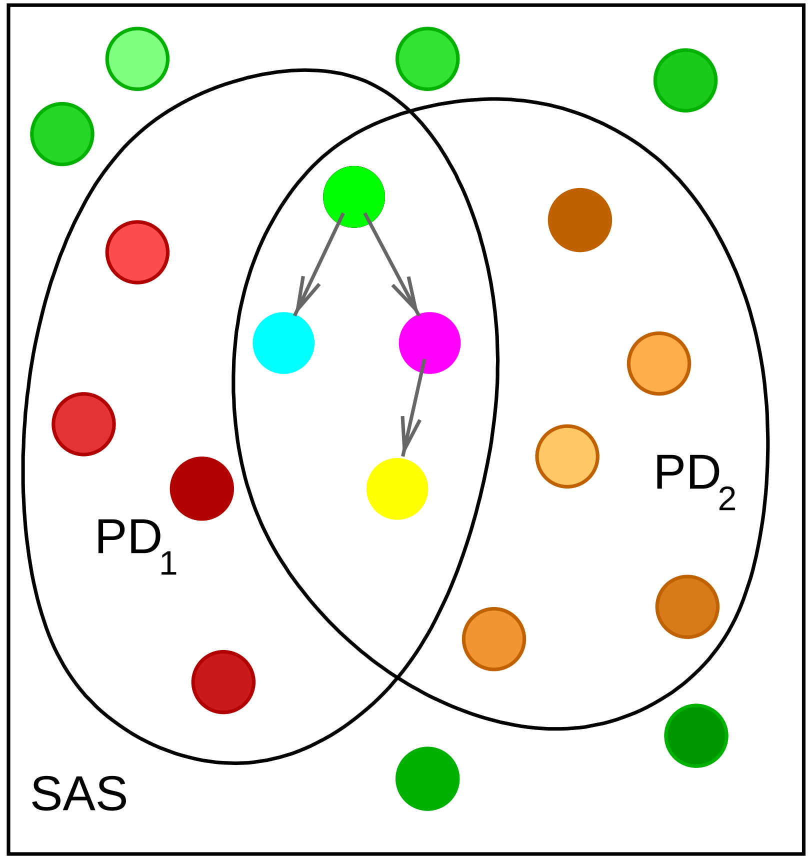

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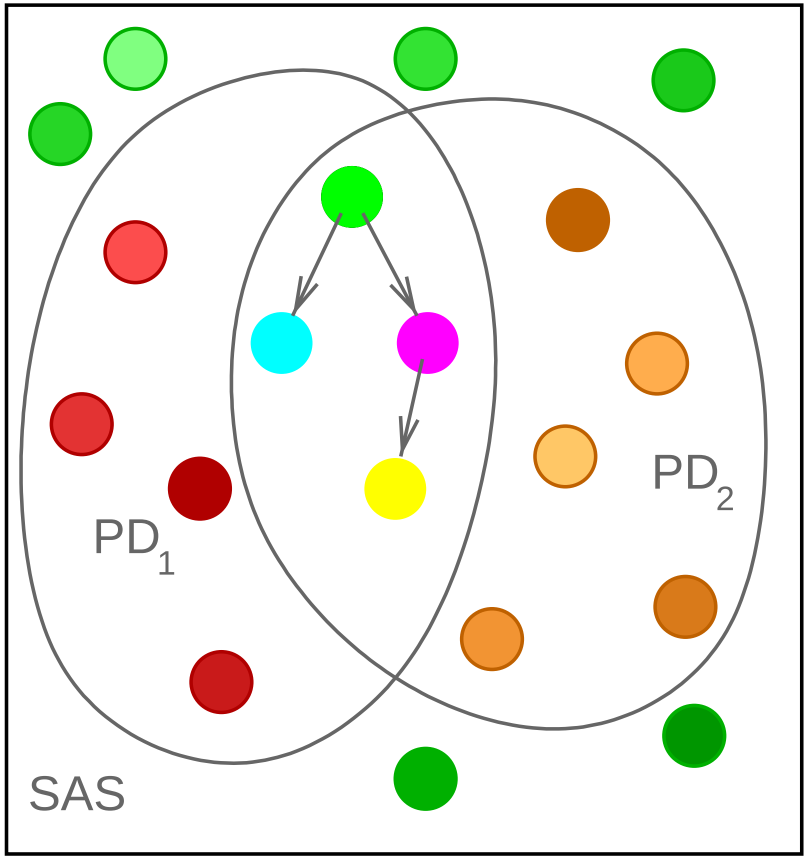

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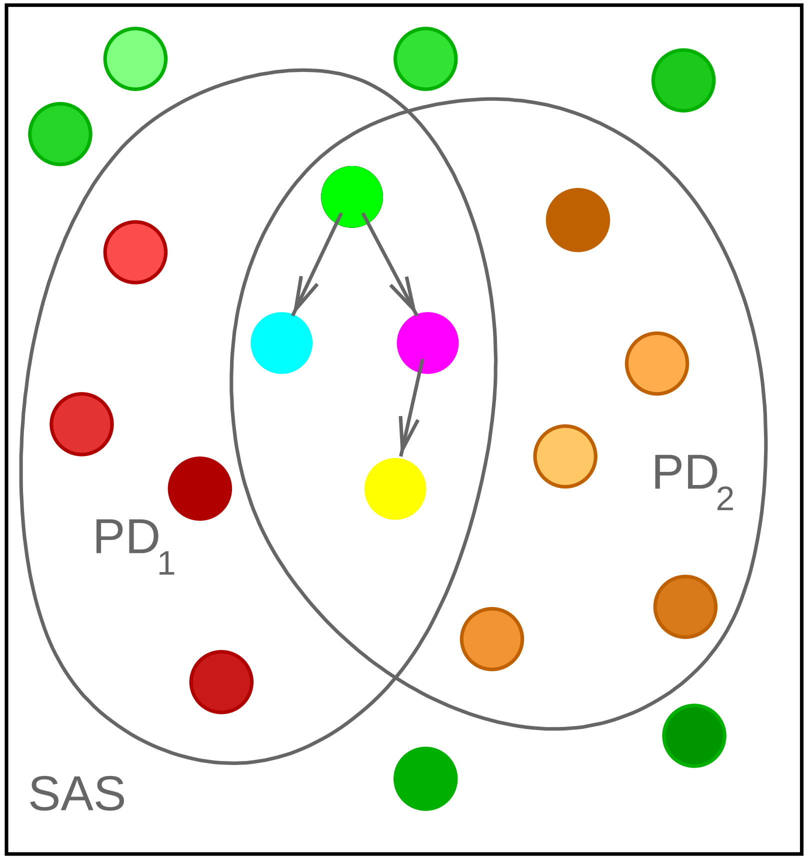

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- Protection domain
  - ➜ defines access and resource rights of a thread
  - ➜ corresponds to a process in traditional OS

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- External Space
  - ➜ address space extern to Iguana's SAS
  - ➜ for legacy support and large processes

Iguana Philosophy

- Small and lightweight
- Strong yet unintrusive protection
- Support for resource management
- Legacy support
- Code and concept re-use

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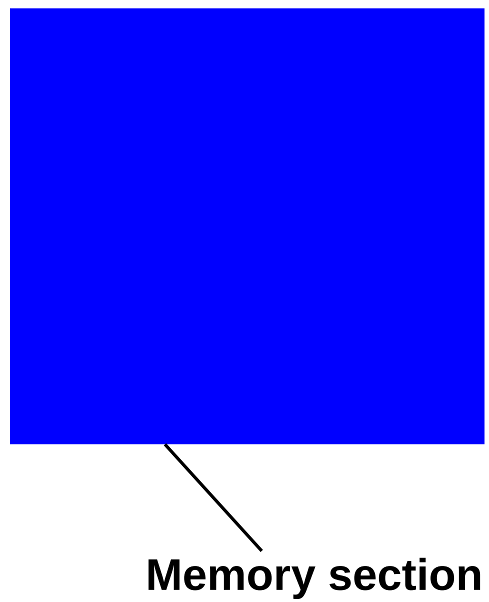

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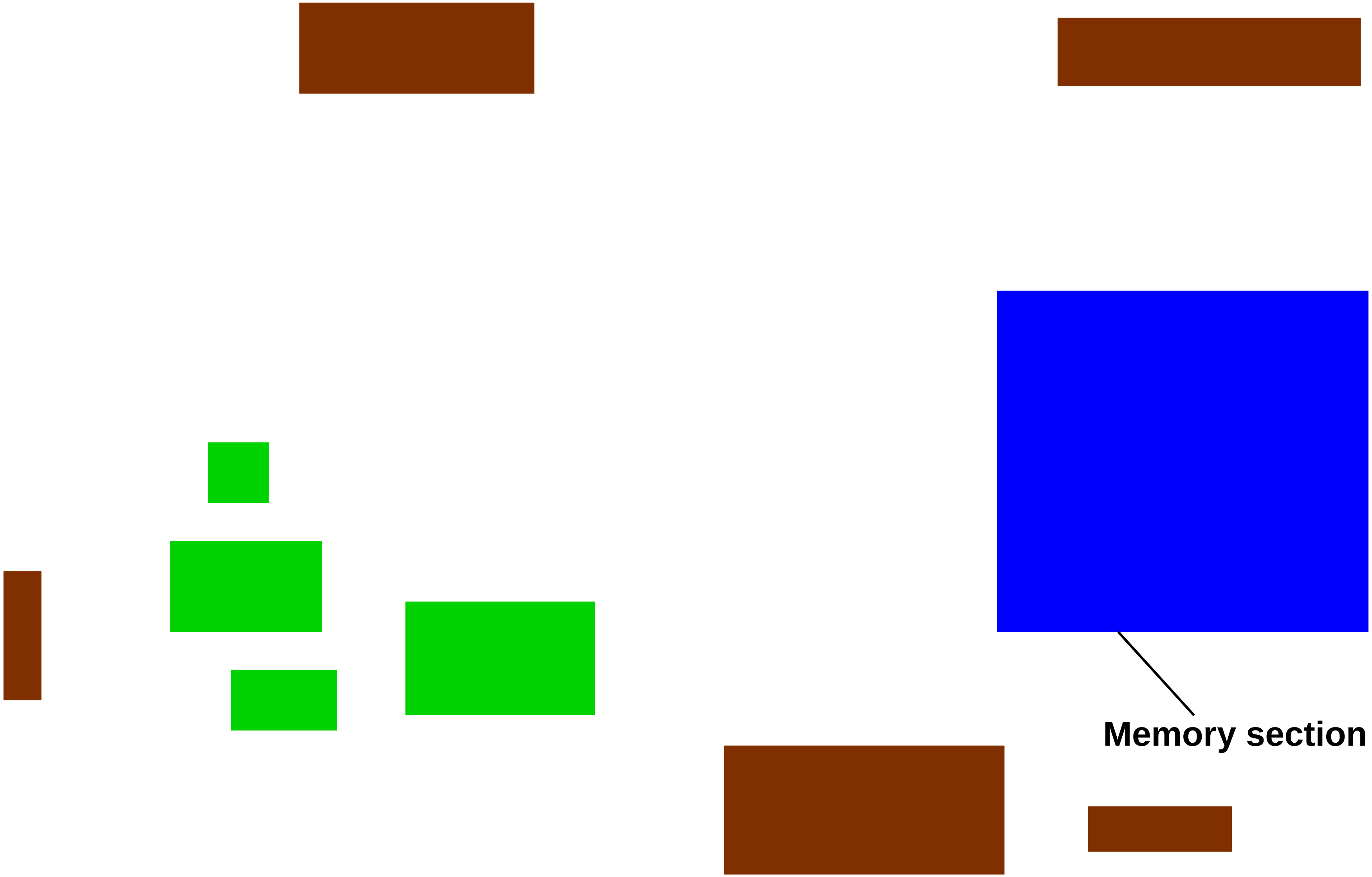

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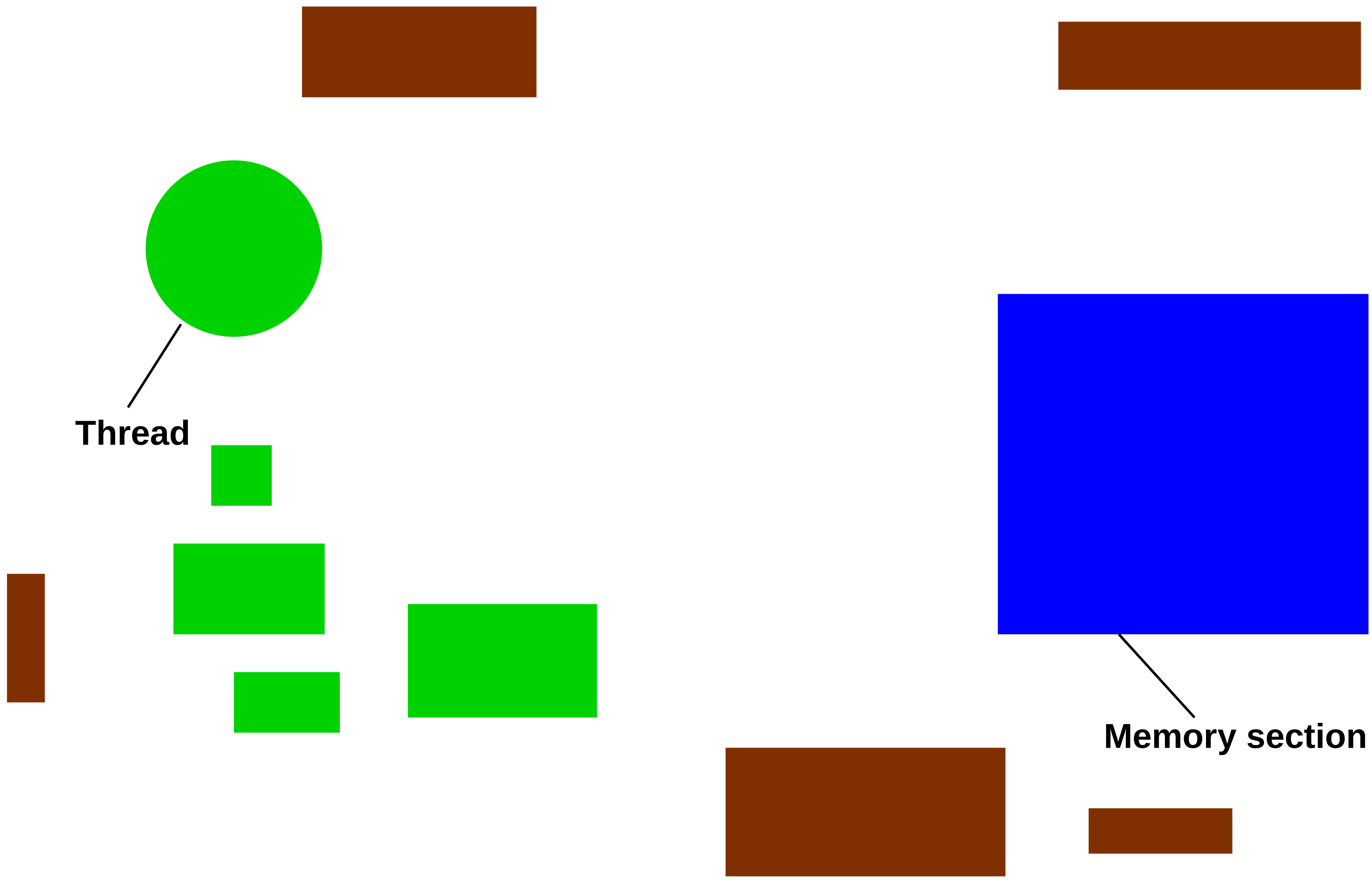

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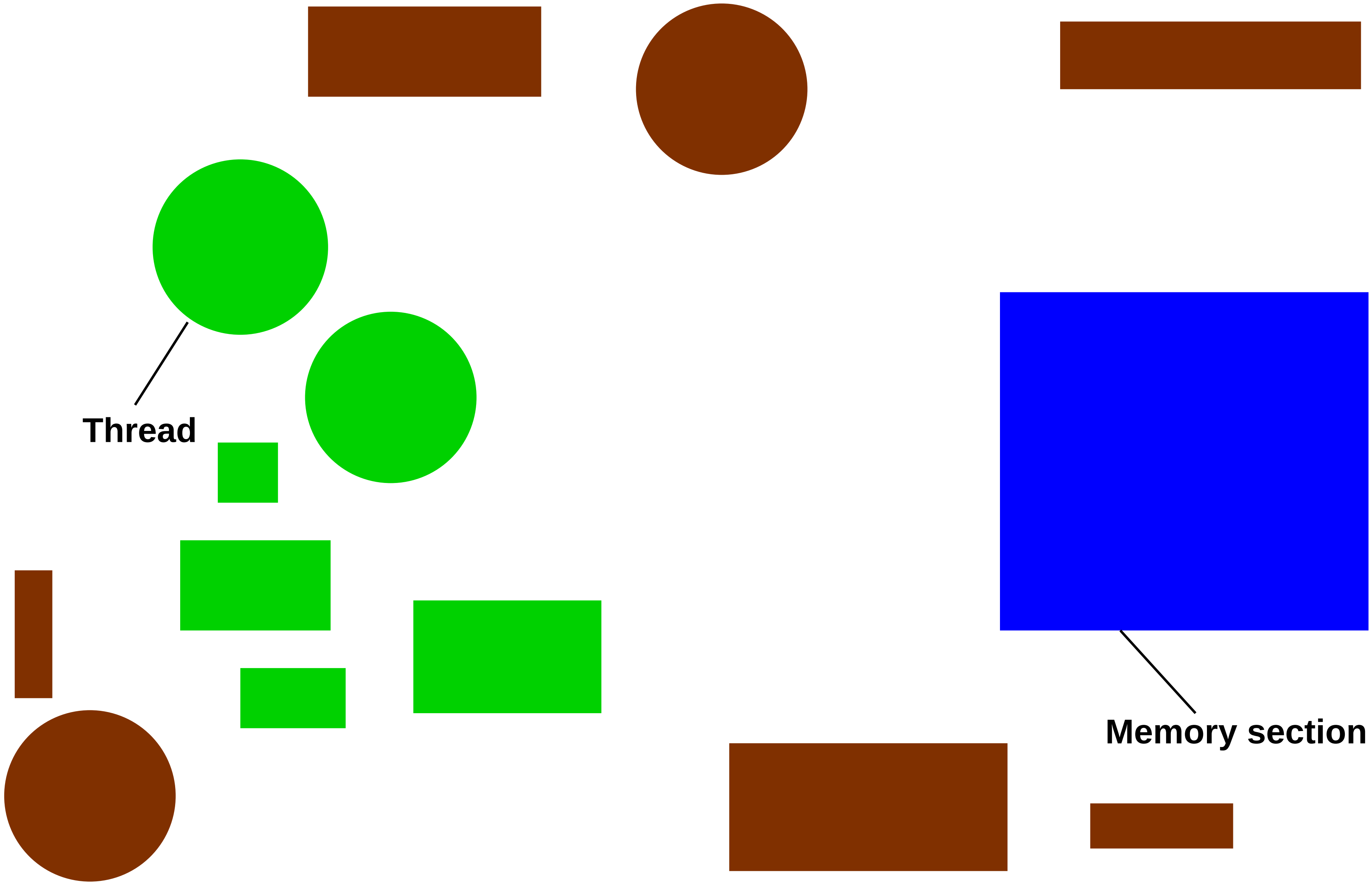

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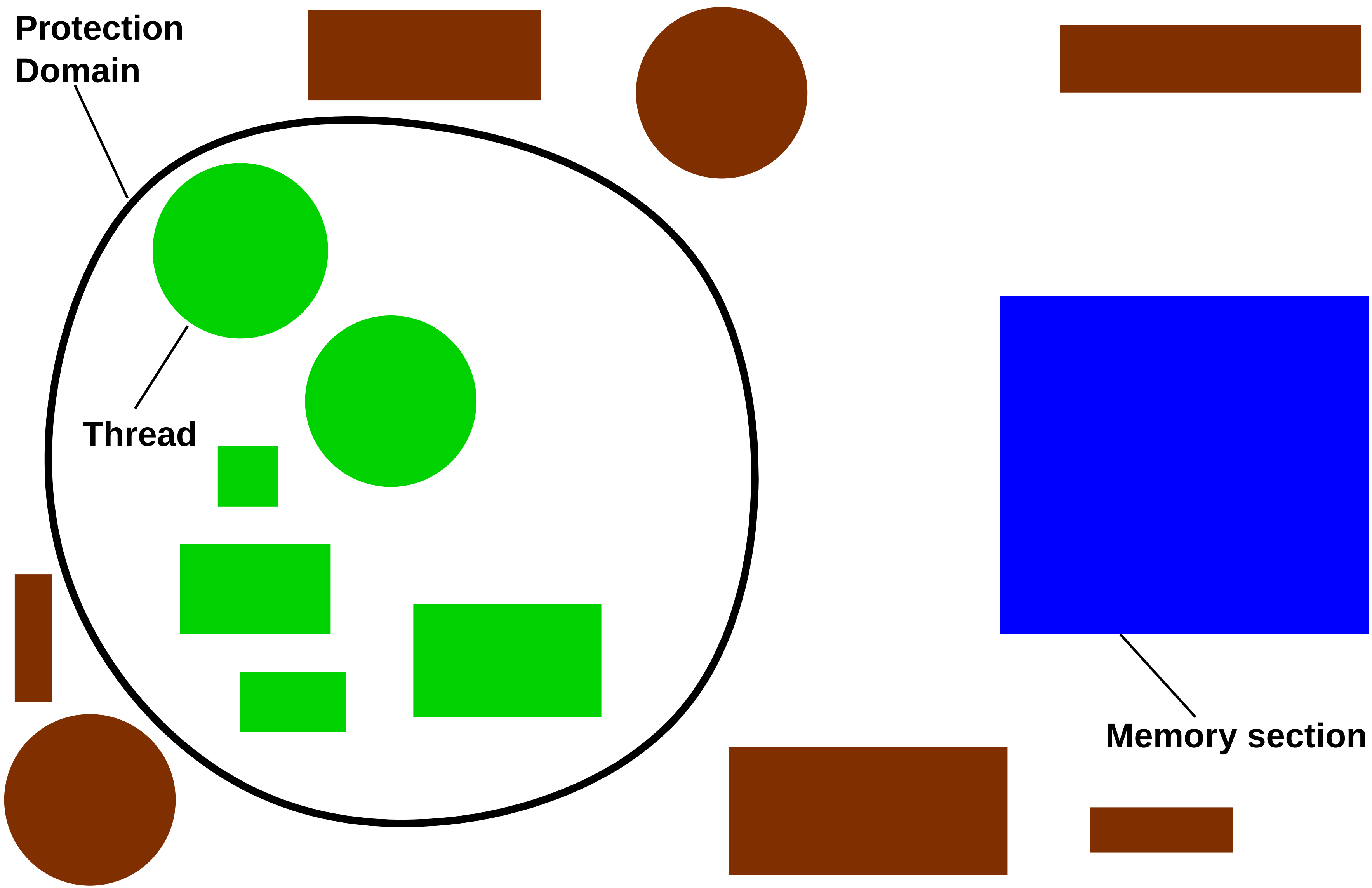

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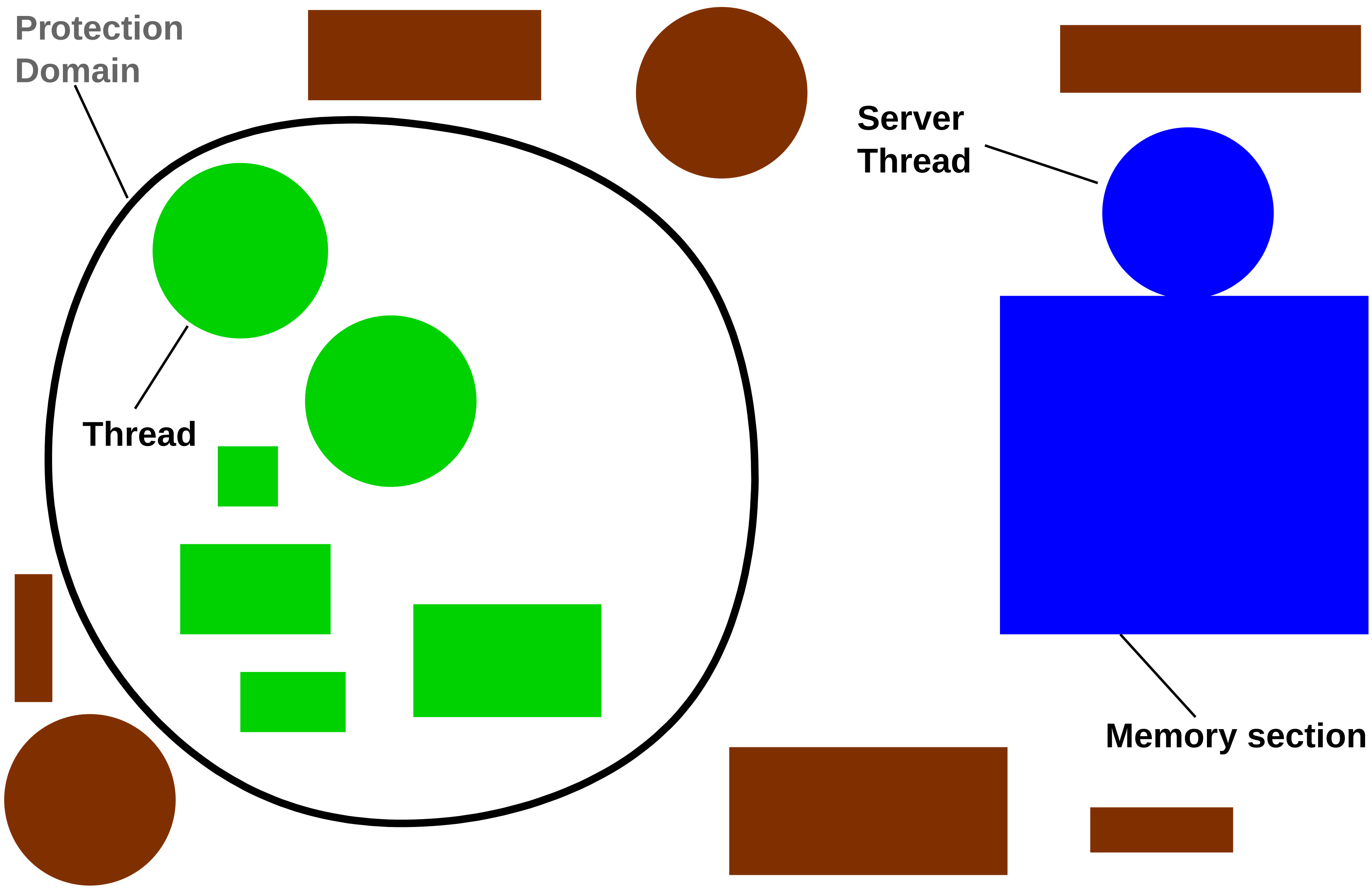

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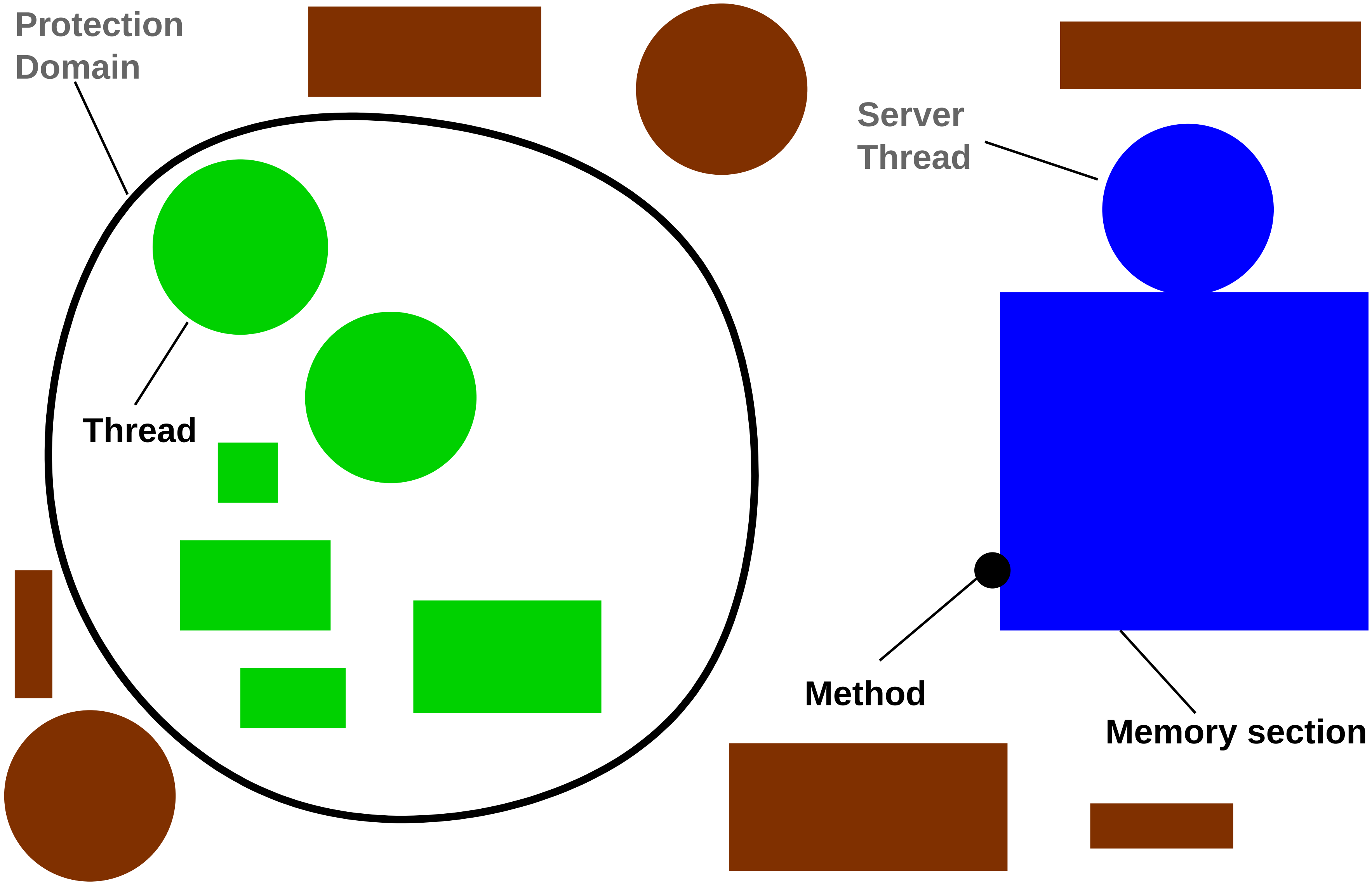

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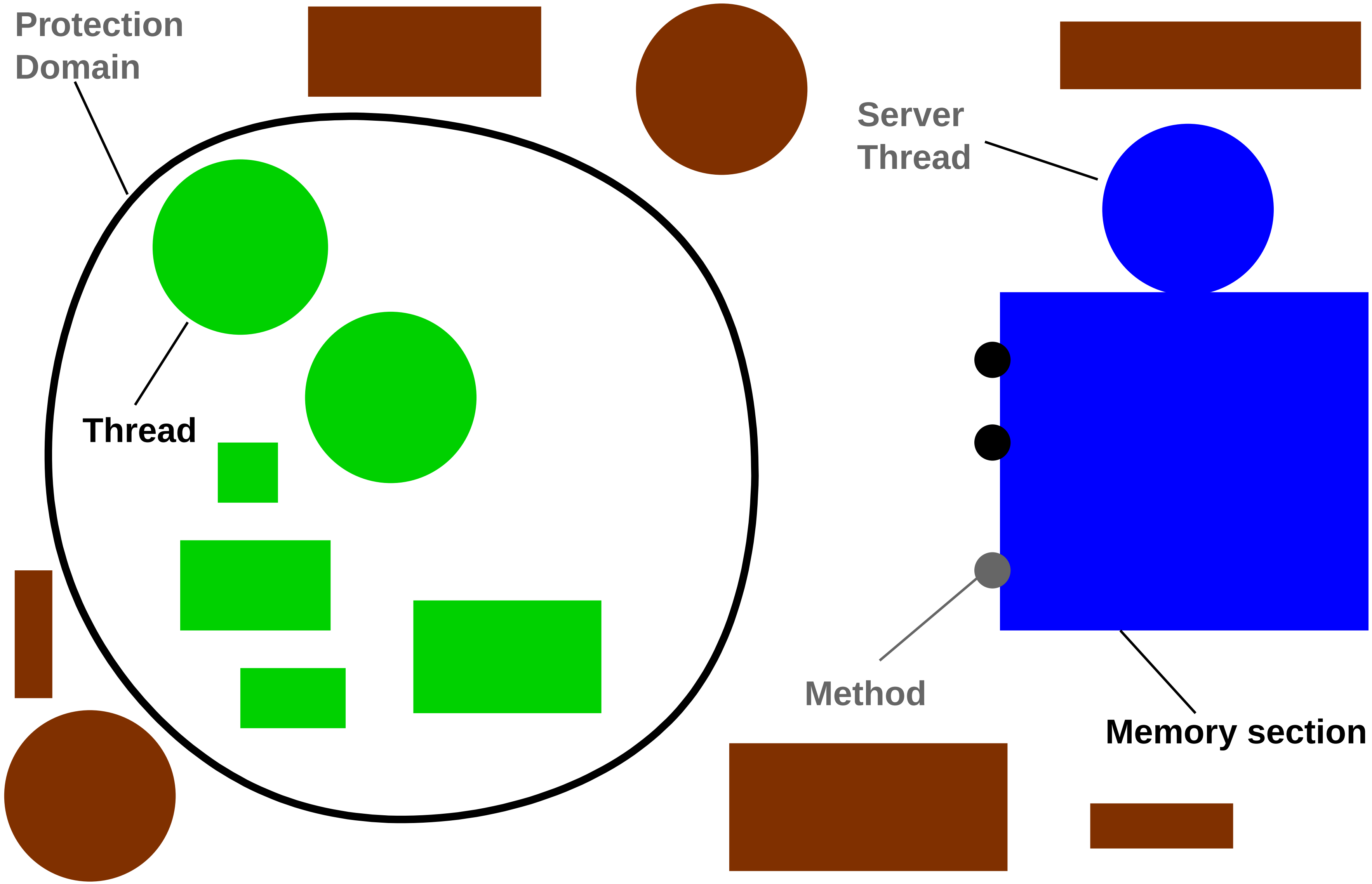

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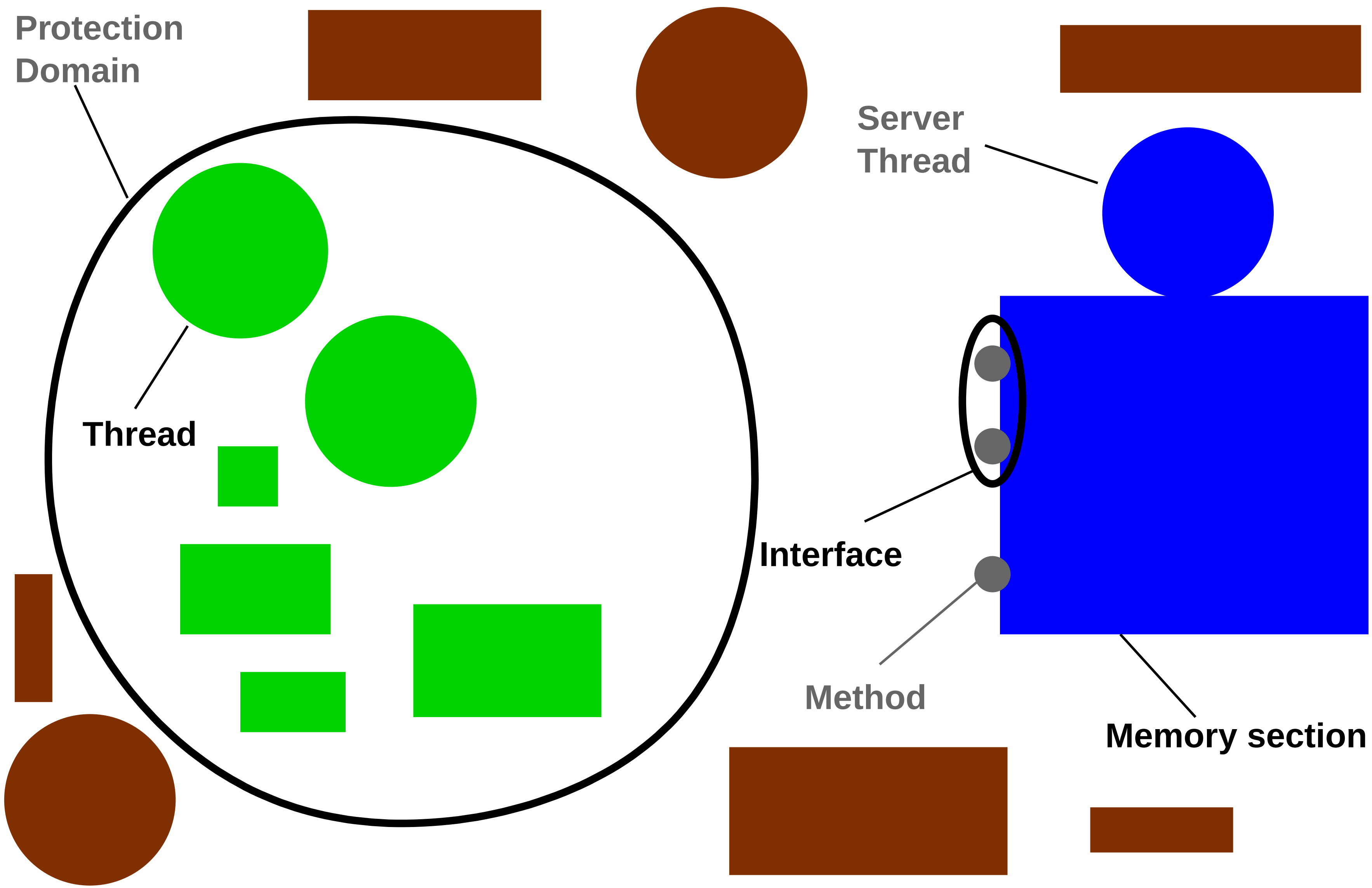

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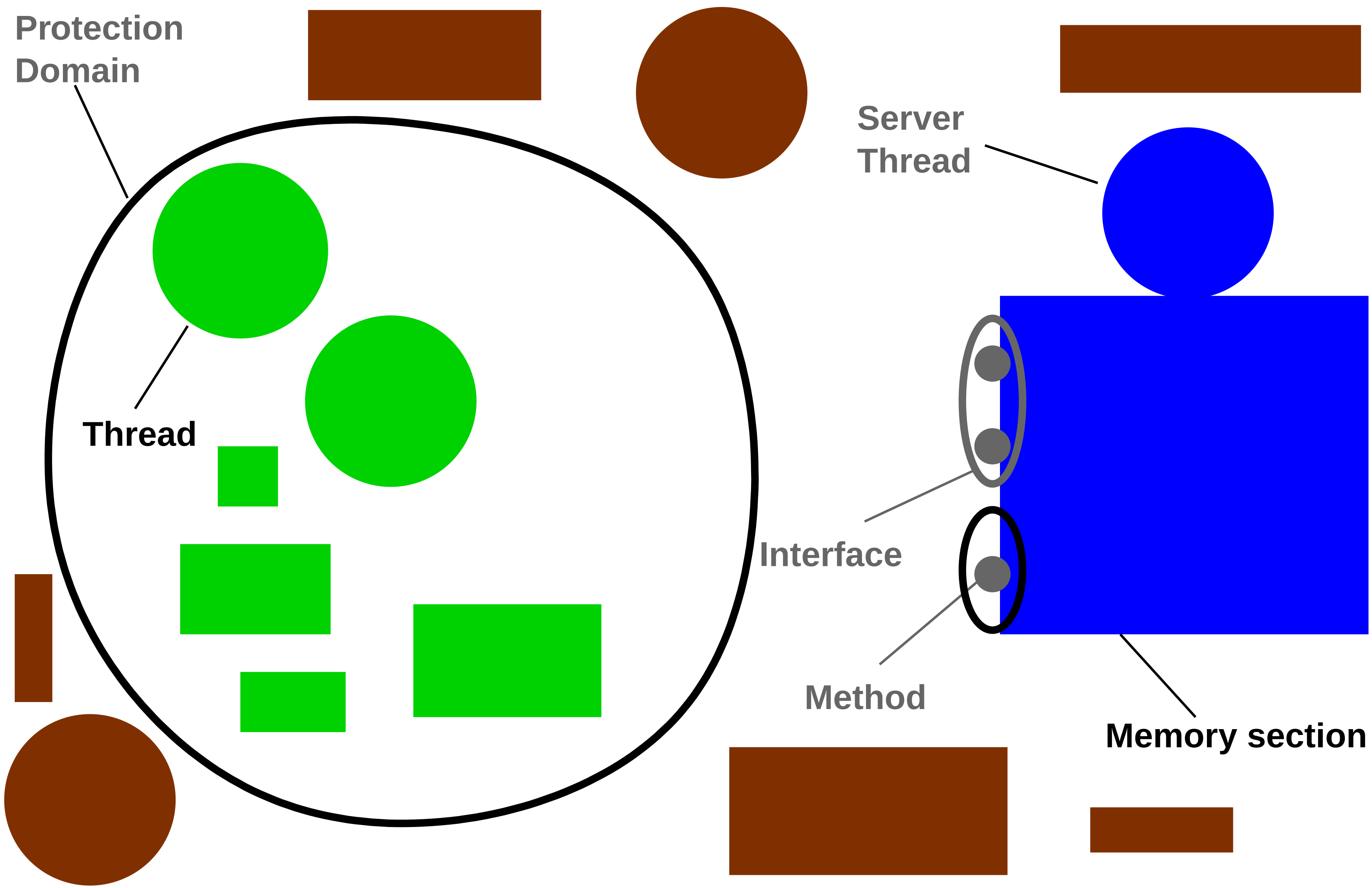

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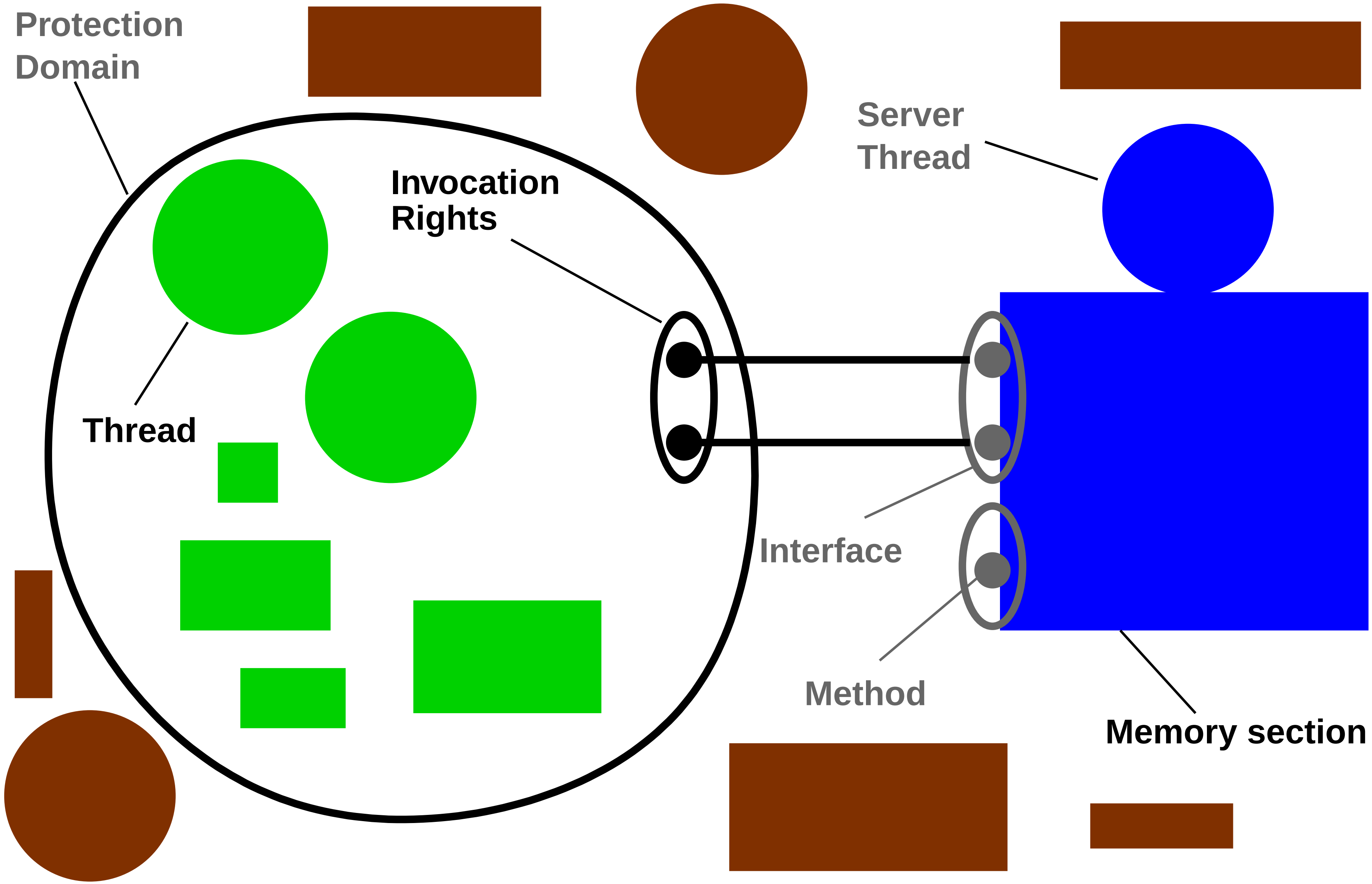

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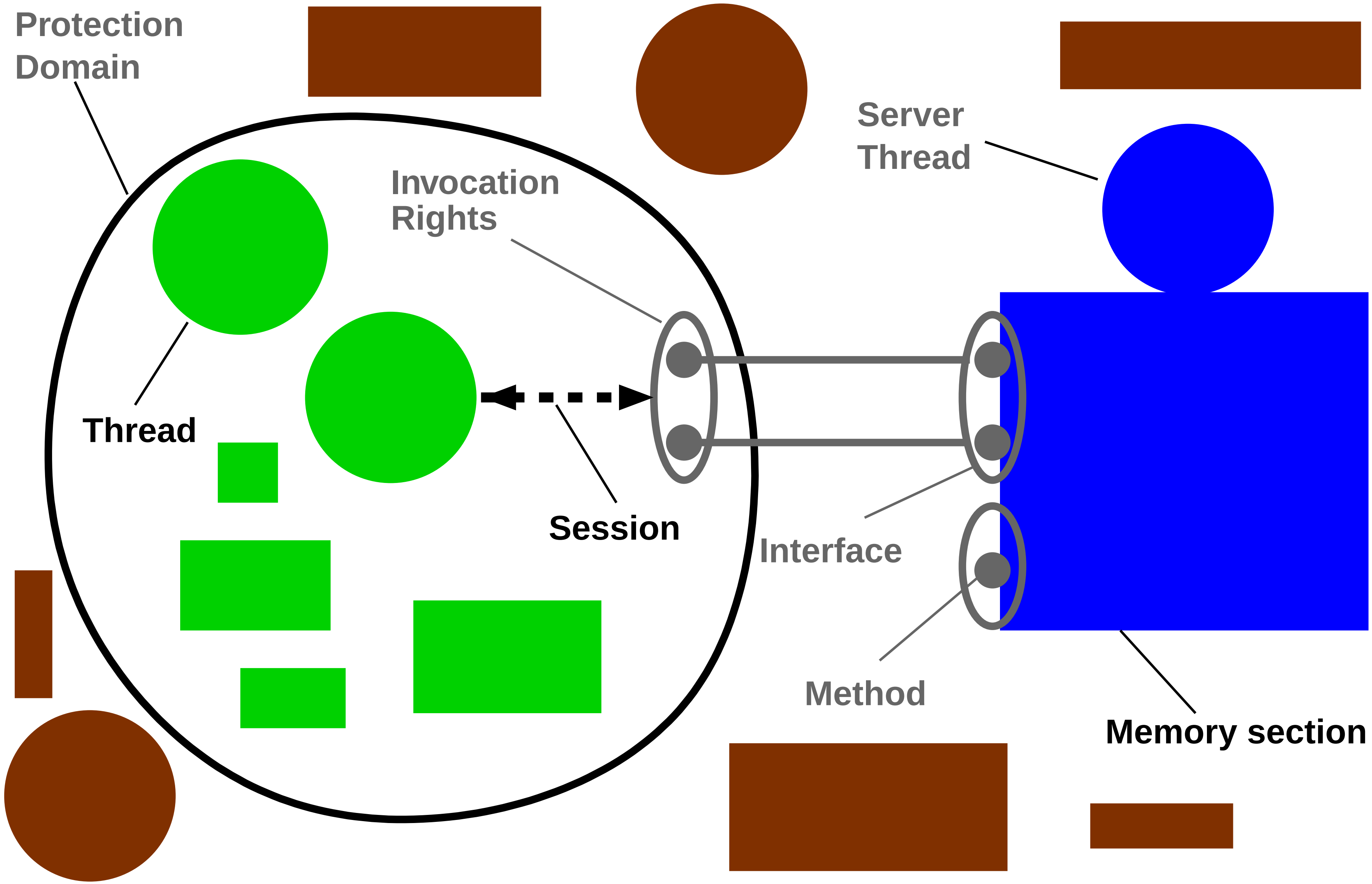

Iguana Objects

- Six kinds of *objects*

1. memory sections
2. threads
3. protection domains (PDs)
4. sessions
5. resource tokens (restoks)
   - ➜ not yet implemented, not covered here
6. external spaces
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- Access controlled by *capabilities*

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- Methods are grouped into *interfaces*
  - ⋆ interfaces also have unique IDs (IIDs) that are OID + interface number
  - ⋆ interfaces have capabilities
    - ➜ grant rights to invoke an interface's methods
  - ⋆ all pre-defined methods belong to separate interfaces
    - ➜ i.e., access is individually protected

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- Client-server model instead of migrating-threads model
  - ➜ more familiar to potential users
  - ➜ avoids some (as yet) unresolved resource management issues
- Aimed at commercial deployment ⇒ more conventional
  - ➜ Mungi is a pure research system
  - ➜ useful for trying out things

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- Two kinds of capabilities in Iguana:

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- Capabilities are only active if stored in PD's *capability lists*
  - ➜ as in Mungi

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    mem_cap = *pd*->new_mem(*size*);

- Memory sections are the only objects that support user-defined methods

  ➜ others have pre-defined (standard) methods only

- Used to provide encapsulated services:
  - ⋆ service = memory (data) + server (thread) + methods

MEMORY SECTIONS...

- To create a service:
  - ⋆ register a server thread on memory section

    base`->new_server(`*thread_id*`);`

    ➜ *base* is the base address (OID) of the memory section
  - ⋆ register interfaces (user-defined methods)

    base `=` *iid*`->new_cap();`

    ➜ *iid* refers to number of new interface

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    ```
    base = iid->new_cap();
    ```

    ➜ *iid* refers to number of new interface
- Registering interfaces supports user-defined methods
  - ⋆ remember: each interface can have one or more methods

    ➜ interface number only interpreted by server

    ➜ similarly, the method number is an opcode delivered to the interface
  - ⋆ IIDs and method numbers allocated by system implementor

    ➜ part of the service's interface protocol

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  - ⋆ subjects them to same protection mechanisms as other methods
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  - ⋆ subjects them to same protection mechanisms as other methods
  - ⋆ no actual methods exist corresponding to those operations
- Further pseudo-method is *clist* (C)
  - ⋆ allows holder to add an object to the Clist array

THREADS

- Iguana threads are essentially L4 threads:
  - threads within same PD operated on by plain L4 syscalls
    - ➜ correspond to local L4 threads (i.e., same L4 AS)
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- Certain operations require privileges
  - ⋆ e.g. thread creation and deletion done by privileged L4 `ThreadControl()` call
- Done by Iguana on invocation of appropriate methods

Thread Operations

- Thread creation:

  thread_cap `=` *pd*`->new_thread(&`*l4_tid*`);`

  - returns two kinds of thread IDs
    - Iguana thread ID (*tid*), part of the *thread_cap*
      - ➜ used for protection and other Iguana-specific purposes
    - L4 thread ID (*l4_tid*)
      - ➜ used for L4 syscalls

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- New thread created *inactive*

  ⋆ can be activated by:

  - ➜ L4 syscall `ExchangeRegisters()` (local threads only)
  - ➜ Iguana method `tid->start(ip,sp)`

THREAD OPERATIONS...

- Obtain L4 thread ID

➜ `l4tid = tid->l4_tid();`

- Obtain own thread ID

➜ `tid = myself();`

- Obtain protection domain of thread

➜ `pd = tid->domain();`

- Obtain and modify scheduling parameters

➜ `tid->schedule_info(&info);`

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    - ➜ **Note:** This is likely to change
  - ⋆ Iguana informs the server by invoking its notification method

```
server->session_created(pd);
```

  - ⋆ Iguana notifies remaining partners if the session is destroyed

```
pd_or_server->session_destroyed(session);
```

IGUANA CAPABILITIES

- Iguana capabilities are user-level objects
  - ➜ *password capabilities*, consisting of OID and password

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  - ➜ Length of password is configurable (normally $\geq$ 64 bits)

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- Same model as in Mungi
  - ➜ implicit presentation
  - ➜ two-level structure (Clists caps array, Clists)
  - ➜ same confinement approach

External Spaces

- External spaces are “raw” L4 address spaces
  - ➜ not part of Iguana SAS
- Provided to deal with restrictions of Iguana model
  - ➜ 32-bit address space may not be large enough to share between all protection domains
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- External spaces come at a cost
  - ⋆ unable to make full use of fast address-space switching on ARM
  - ⋆ not well integrated with Iguana world
    - ➜ no fine-grained access control provided by Iguana capabilities
    - ➜ not allowed to communicate with any PD other than creator
      - ➜ not even with Iguana — cannot invoke methods
      - ➜ enforced via L4 redirectors

External Spaces — Operations

- Creation requires explicit specification of KIP and UTCB address

```
es = pd->new_es (kip, utcb_area);
```

- Thread creation also requires arguments similar to L4

```
l4tid = es->new_thread(pager,scheduler,starter,utcb);
```

HARDWARE ACCESS

- Device drivers need to access raw hardware features
- Iguana provides a (static) `hardware` object for this
  - ⋆ physical memory access:

    ```
    hardware->back_mem(adr, p_adr, caching);
    ```

    ➜ maps the memory section (`adr`) to the specified physical address with specified caching attributes
  - ⋆ interrupt association:

    ```
    hardware->register_interrupt(tid,irq);
    ```

    ➜ registers the specified thread as the handler of the specified interrupt

RESOURCE TOKENS

- Iguana’s resource management mechanism
- Note: presently this only exists conceptually
  - ➜ details of the model still need to be worked out
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  - ➜ however, model is based on our experience with a similar model in Mungi
- Basic idea: all resources have a price that must be paid by the user
- Model provides great flexibility for defining charging details
- Generalisation of Mungi bank accounts

WOMBAT: A PORTABLE LINUX SERVER ON L4

MOTIVATION

- Provide Linux API
- Support architectures other than x86
- Be easily maintainable
- Integrate with Iguana

LEGACY APIs ON L4

- Microkernel, like L4, provides mechanisms, not services
  - ➜ services implemented by user-level server
  - ➜ microkernel is OS agnostic
  - ➜ can, in principle, provide any OS API (OS “personality”)
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  - ➜ Mach Unix server
  - ➜ IBM Workplace OS (Mach-based)
- Attributed to poor Mach IPC performance, large cache footprint

Porting Monolithic Kernels: Pros

- Code reuse: Existing services
- Code reuse: Legacy support
- Coder reuse
- Buzzword reuse

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  ➜ can use existing code unchanged (file systems, network stacks, drivers, ...)
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- Buzzword reuse
  - ➜ can jump on Linux bandwagon while really doing something more sensible...
  - ➜ good PR value ;-)

Porting Monolithic Kernels: Cons

- Performance
  - ⋆ Microkernel inherently adds overhead
    - ➜ microkernel-mediated rather than direct access to hardware
    - ➜ IPC to server (4 mode switches) rather than syscall (2 mode switches)

$\Rightarrow$ Legacy system on L4 will **always** be slower than native!

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- ⋆ Question is: *How much slower???*

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- Main-stream systems have notoriously poor real-time support
  - ➜ typically unsuitable for hard real time

Hybrid Systems: Best of Two Worlds?

- Legacy server and native apps running side-by-side
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- How about performance?
  - ➜ L4 primitives much faster than Mach and others
  - ➜ fast enough?

L4 on Linux: History

L^4Linux

- First port of Linux kernel to L4
- Done for ix86 at Dresden [SOSP 97]
  - ⋆ modified architecture-specific part of Linux to use L4 syscalls
  - ⋆ binary compatibility: syscall redirection to Linux server
    - ➜ syscall exception delivered to L^4Linux via exception IPC
  - ⋆ better performance using modified libc
    - ➜ syscall trap replaced by L4 IPC to Linux server
  - ⋆ re-done for 2.2, 2.4, 2.6
    - ➜ L^4Linux implementation highly dependent on Linux internals
    - ➜ significant effort for forward porting (start from scratch each time)

WOMBAT LINUX SERVER

- Done at NICTA 03–04
  - ➜ done from scratch, independent of Dresden work
- Portable between architectures
  - ➜ based on Iguana
  - ➜ presently runs on x86, ARM, MIPS64
  - ➜ MIPS64 supports 32-bit and 64-bit executables

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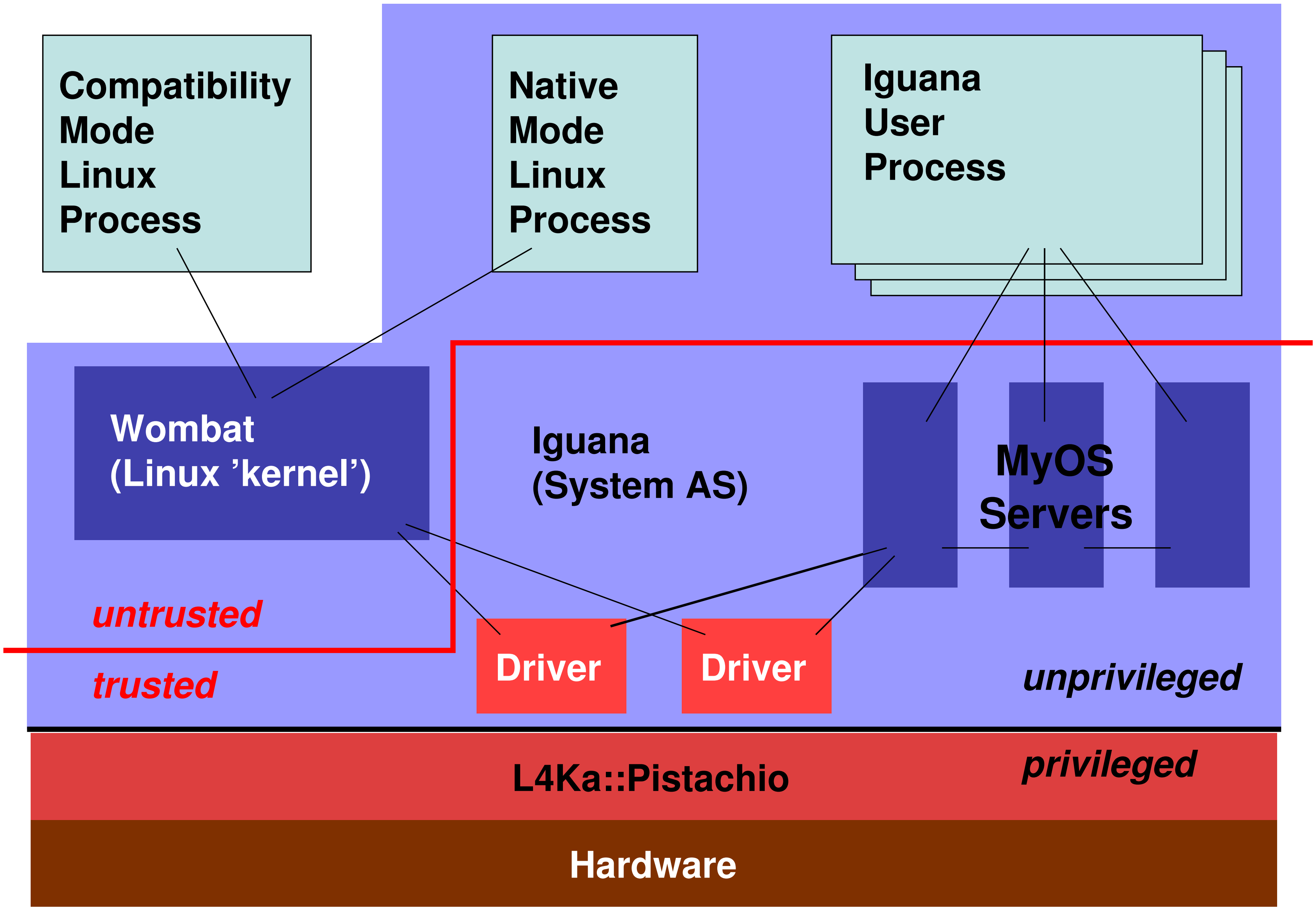
  - ➜ MIPS64 supports 32-bit and 64-bit executables
- Much reduced dependence on Linux internals
- Binary compatibility via syscall redirection
- Proper Linux scheduling of Linux apps
- Potential to achieve good performance on ARM

A SYSTEM RUNNING WOMBAT



WOMBAT IMPLEMENTATION

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    - ➜ third is `printk` (additional early debug output)
  - ⋆ tracked head revision of Linux from 2.5.x to 2.6.4
    - ➜ now at 2.9, will go forward soon

PAGE FAULTS AND EXCEPTIONS

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  - ⋆ is L4 pager and exception handler for Linux processes
  - ⋆ Linux “syscalls” are L4 exceptions
  - ⋆ other exceptions are reflected back as Linux signals
- Have single runnable Linux user process per CPU, unlike L^4Linux
  - ⋆ differs from Dresden/Karlsruhe L^4Linux approaches
  - ⋆ helps to maintain Linux scheduling behaviour

System-Call Processing

- Access to application memory by Wombat:
  - ⋆ provide `copy_to`/`copy_from` functions
  - ⋆ look up page table and find page(s) in server's memory pool
  - ⋆ on MIPS could instead run Wombat in supervisor mode
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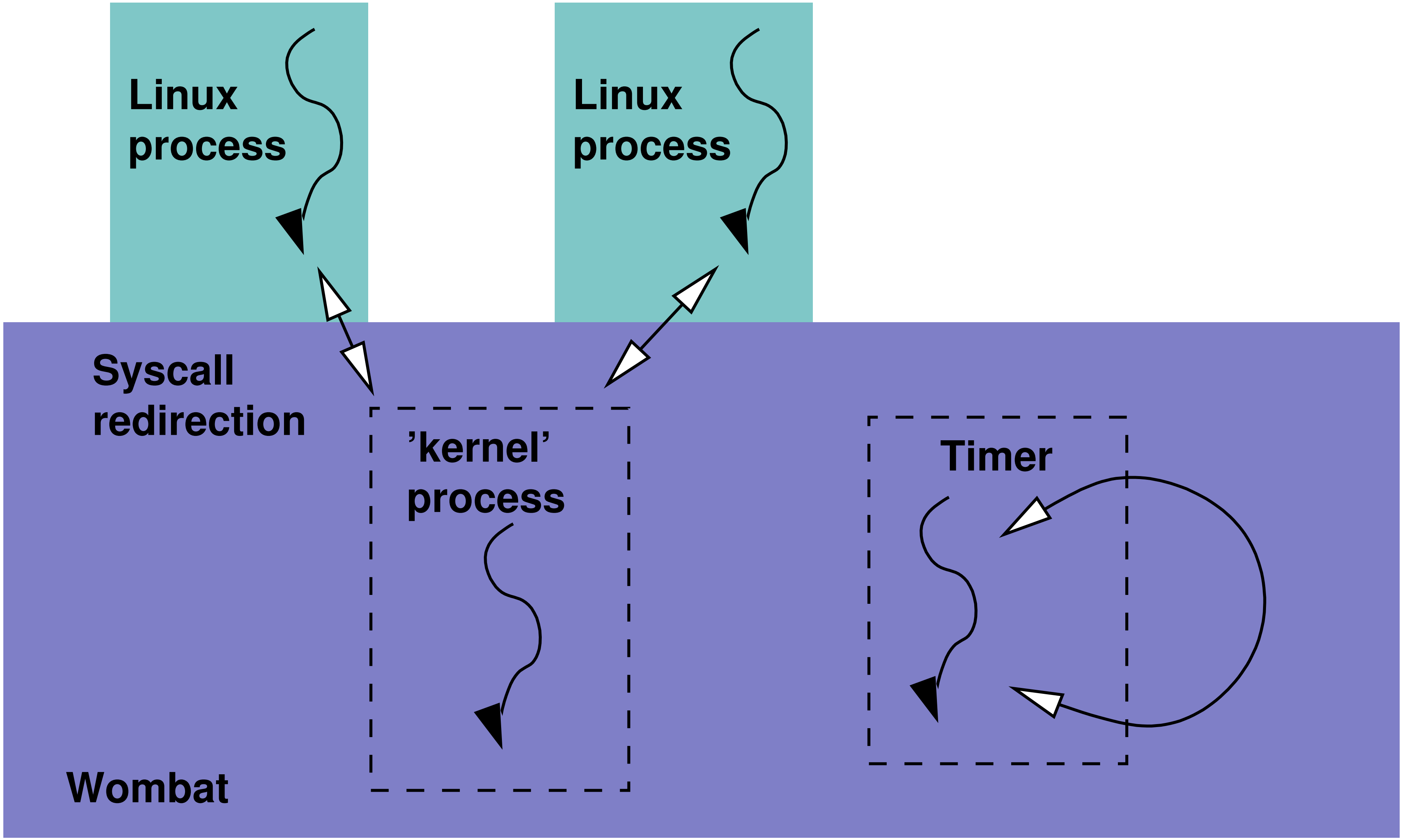
- Signal processing is architecture dependent

➜ emulates Linux signal handling

LINUX PROCESSES



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- Scheduling happens when Linux process enters kernel
  - ⋆ checks reschedule flag, if set:
    - ➜ invokes Linux scheduler
    - ➜ perform context switch, reset reschedule flag

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    - ➜ processes run normally slightly longer than Linux time slice
    - ➜ CPU-bound process runs up to twice as long
    - ➜ Should be able to get exact Linux scheduling (but at a cost!)

LINUX IDLE TASK

- Linux's idle task executes `cpu_idle()`
  - ⋆ architecture-specific function
  - ⋆ in Wombat this IPCs to the "kernel" thread
  - ⋆ that one just sleeps until the next time tick or interrupt
  - ⋆ could just as well be made to go into a low-power mode

WOMBAT PERFORMANCE (PRELIMINARY)

			trampoline		IPC	
Benchmark	**Server**	**Linux**	**L4**	**ratio**	**L4**	**ratio**
`getpid()`	L4Linux	1.68	9.66	3.7	3.95	2.4
	Wombat	0.41	1.94	4.7		
2-proc ctxsw	L4Linux	7.0	18.2	2.6	16.2	2.3
	Wombat	4.03	9.66	2.4		
pipe	L4Linux	29.0	69.4	2.4	22.2	1.8
	Wombat	6.3	16.5	2.6		

- ➜ L4Linux 2.0 on 133MHz Pentium [SOSP 97], some improvements since
- ➜ Wombat 2.6 on Pentium-4 Xeon 2.66Ghz, *unoptimised*
  - ➜ overhead should be smaller on RISC processors

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    - ➜ ... by restricting capabilities to the `hardware` object
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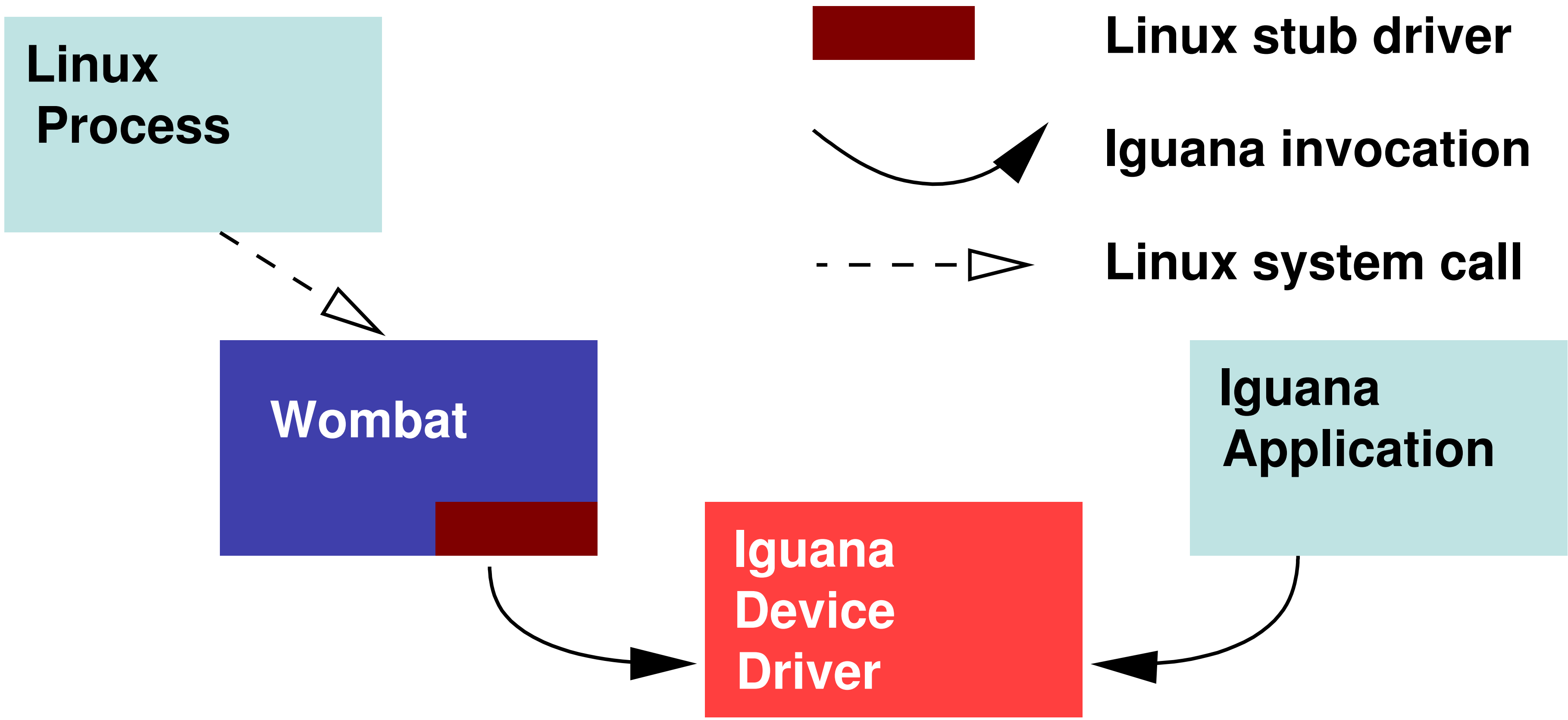
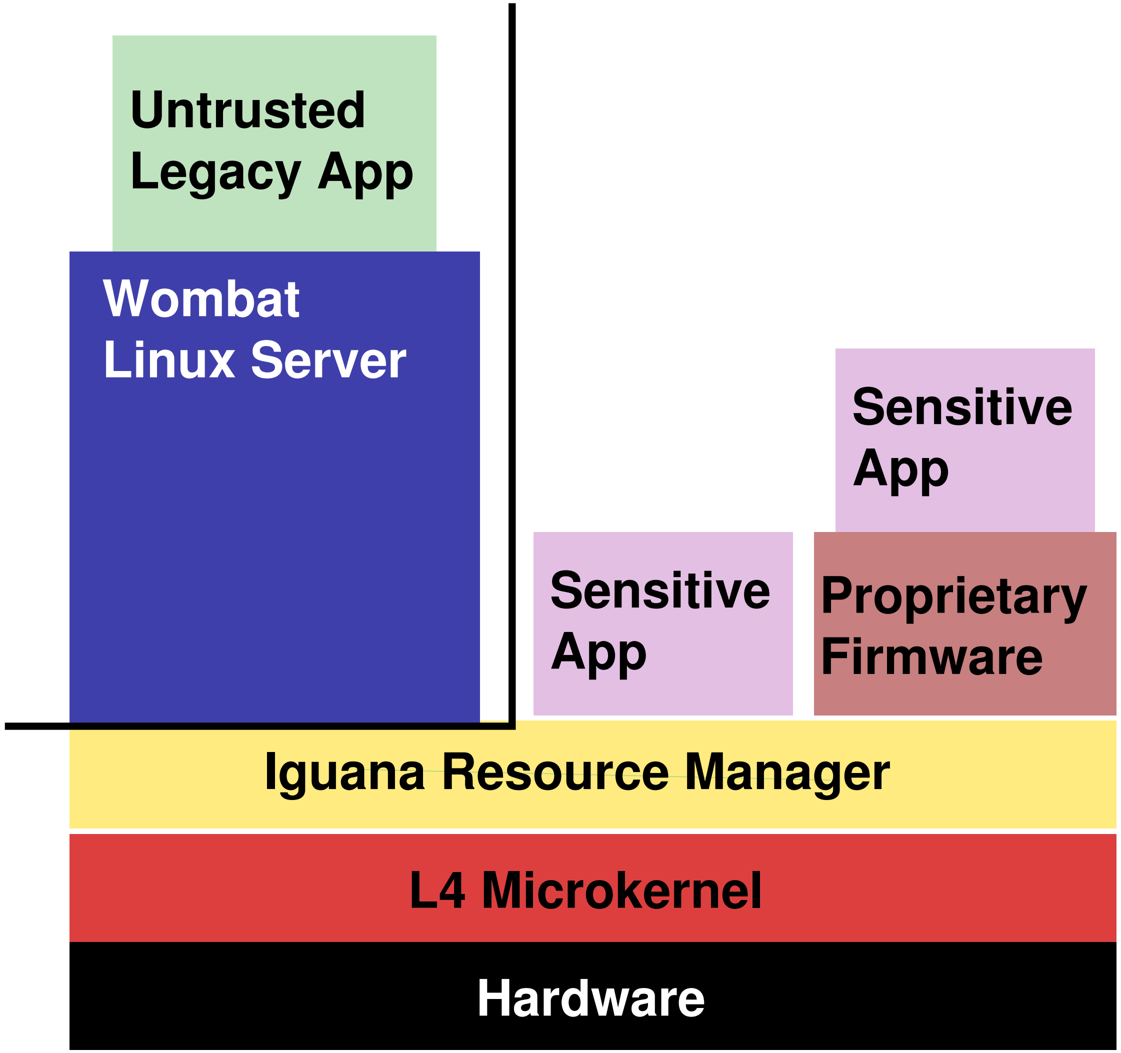
- Driver is then able to operate the hardware
- Provides methods as per Iguana driver protocol

Sharing Iguana Device Drivers with Wombat



- Wombat has stub driver module
  - ➜ invokes Iguana driver
  - ➜ sample exists for console

TARGET SYSTEM ARCHITECTURE



Similar to Dresden DROPS system

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  - ➜ proper SMP implementation
  - ➜ support for heterogeneous multiprocessors (rSoC)
  - ➜ design and implementation of proper resource management

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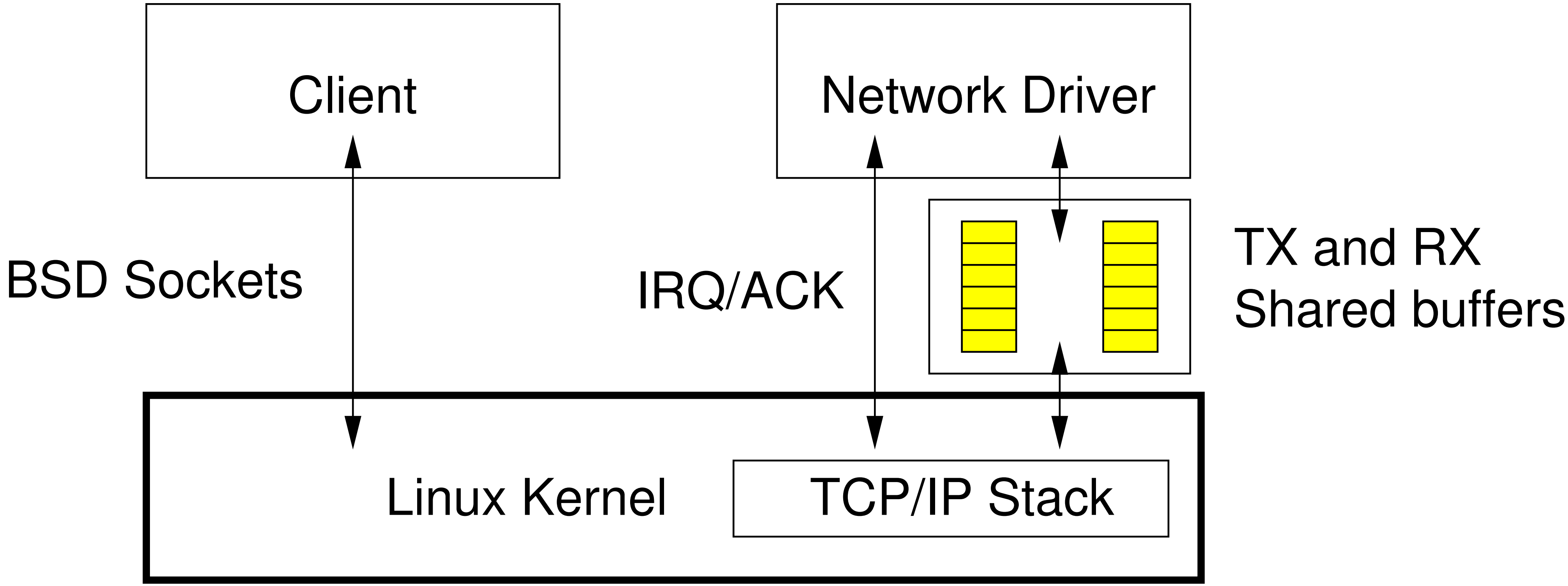
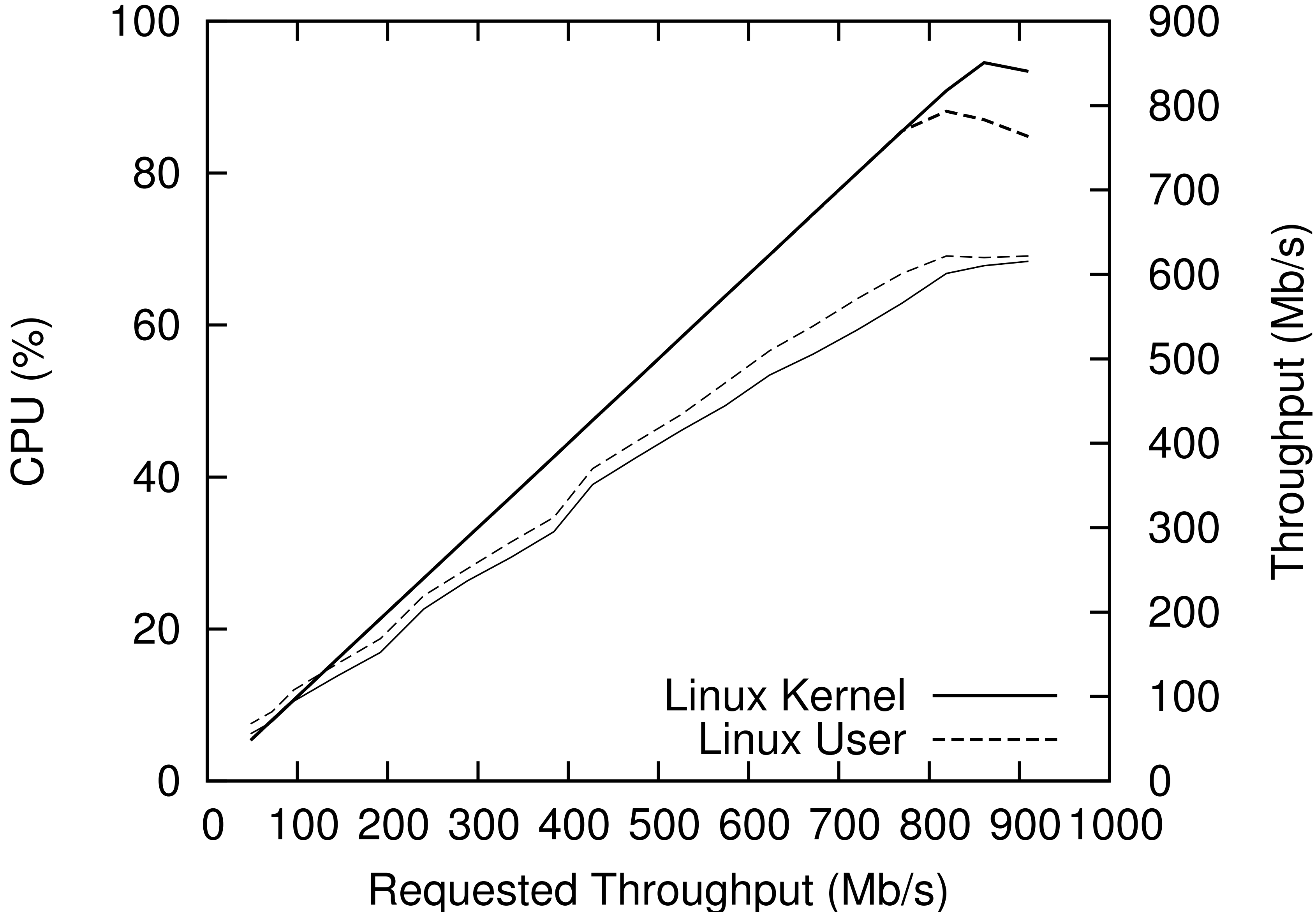
- L4 IPC performance is very high
  - ⋆ with well-designed driver interfaces can achieve good performance

USER-LEVEL DEVICE DRIVERS ON LINUX



Benchmarking setup

USER-LEVEL DEVICE DRIVER PERFORMANCE



Gigabit Ethernet echo on 900MHz Itanium-2 with 66MHz 64-bit PCI

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- Collaboration with Dresden, Johns Hopkins (Jonathan Shapiro)
  - ➜ Kevin Elphinstone, 1 staff, students

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  - feasibility study
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- Operates on a “slice” of the API (address-space management)
  - ⋆ done formal model of (simplified) API slice
  - ⋆ proved some properties (absence of loops in mappings)
  - ⋆ refined specification down to source code
    - ➜ page table operations and simplified mapping database

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COMPONENT-BASED SOFTWARE ARCHITECTURE

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- Collaboration with NICTA Empirical Software Engineering Program
  - ➜ 3 staff, several PhD and U/G students, visitors

SECURE MOBILE CODE

- Combines language and OS techniques for secure execution
- Code may be:
  - ➜ accompanied by a proof certificate establishing its trustworthiness
  - ➜ otherwise sandboxed execution
- Lead by Manuel Chakravarty
  - ⋆ presently working on theoretical foundations
  - ⋆ later to be integrated with Iguana
  - ⋆ requires *configurable protection domains*

GOANNA: STATIC ANALYSIS OF SYSTEMS SOFTWARE

- Model-checking-based tools looking for bugs in kernel & libs
- Collaboration with NICTA Formal Methods Program
- Pilot Project April 05 – March 06
  - ➜ examine state of the art
  - ➜ evaluate existing tools
  - ➜ analysis framework
  - ➜ get experience with model-checking of systems code
  - ➜ develop plan for follow-on project

PROJECT: OS-FRIENDLINESS OF ARCHITECTURES

- Evaluate hardware-dictated OS overheads and trends
- Critical operations
  - ➜ kernel entry and exit
  - ➜ TLB refill
  - ➜ context switch
  - ➜ synchronization primitives
- Hardware characteristics
  - ➜ instruction-set architecture
  - ➜ clock speed
  - ➜ pipeline depth
  - ➜ issue width
- Aim: paper in architecture conference

PROJECT: KERNEL IMPLEMENTATION TRADE OFFS

- Idea: revisit some of Jochen's tricks
  - ➜ virtually- vs physically-addressed TCBs
  - ➜ per-thread vs per-CPU kernel stack
  - ➜ exception IPC vs exception callback
- Question: how much influence of architecture?
- Aim: Conference paper

Project: L4Darwin

- Aim: Mac OS done right
  - ➜ remove Mach
  - ➜ substitute L4
  - ➜ de-privilege Darwin
  - ➜ de-privilege IOkit
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- Aim: exercise for the reader

GELATO: LINUX PERFORMANCE AND SCALABILITY

- VM system performance and scalability
  - ➜ superpage support (particularly Itanium)
  - ➜ NUMA support
  - ➜ guarded page tables for large address spaces
- TCP/IP and NFS throughput and scalability
- NUMA-aware scheduling
- Aims: support
  - ⋆ 1000's of CPUs in a NUMA system
  - ⋆ 1000's of nodes in a cluster
  - ⋆ terabytes of RAM
  - ⋆ support commercial workloads
- Funded by HP and ARC, supported by SGI

Other projects

- Pre-virtualisation
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  - ➜ covered in Week 6
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- Distributed embedded systems
  - ➜ e.g. cars
  - ➜ pilot project SUNswift

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- Simulators
  - ➜ tools for OS development and architecture research
  - ➜ ARM, PowerPC, ...

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- Ample opportunities to participate in cutting-edge research
  - ➜ summer projects
  - ➜ honours theses
  - ➜ PhD theses
  - ➜ employment