Linux, Locking and Lots of Processors

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  - File system model
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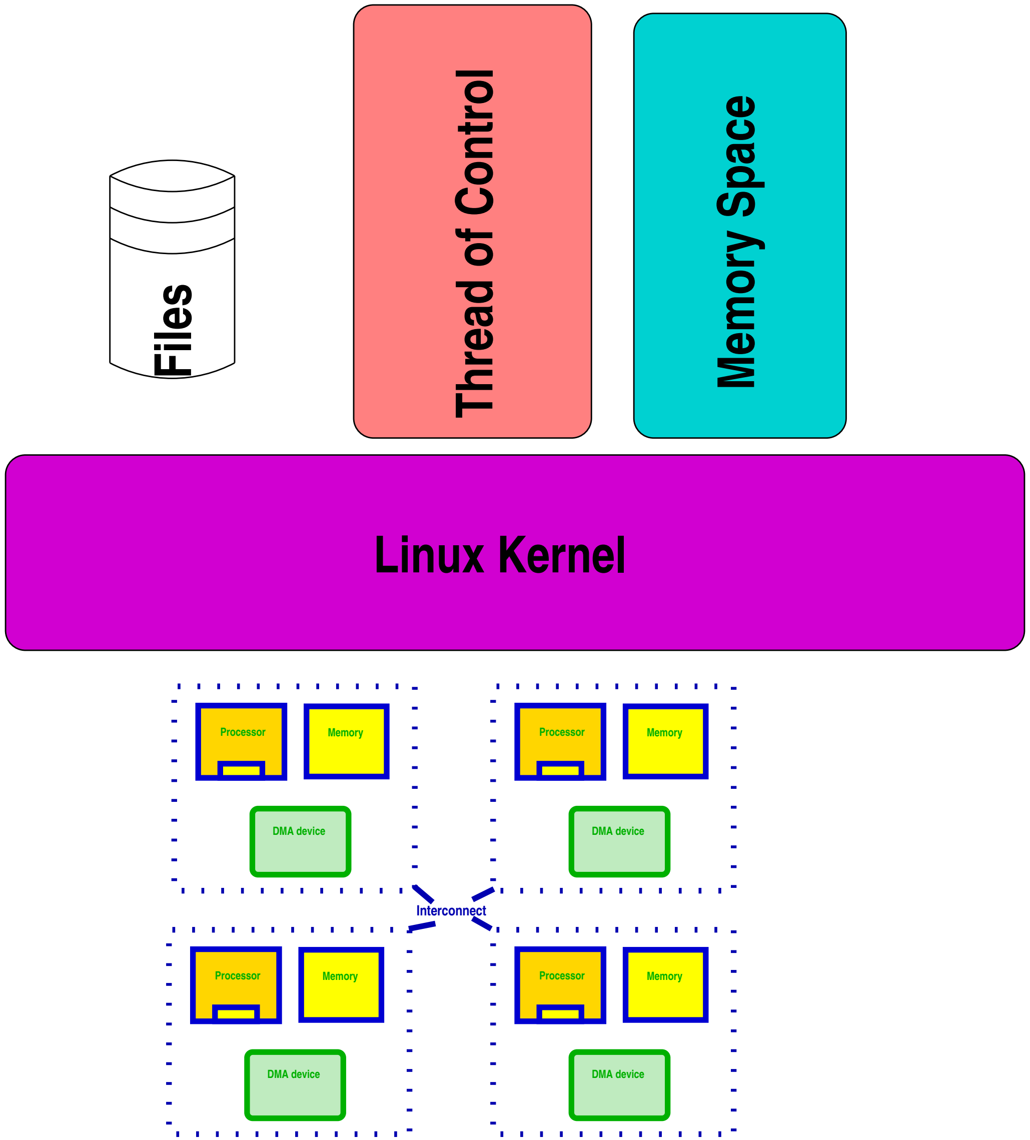
- Additions:
  - Paged virtual memory (3BSD, 1979)
  - TCP/IP Networking (BSD 4.1, 1983)
  - Multiprocessing (Vendor Unices such as Sequent's 'Balance', 1984)

Abstractions



Process model

- Root process (`init`)
- `fork()` creates (almost) exact copy
  - Much is shared with parent — Copy-On-Write avoids overmuch copying
- `exec()` overwrites memory image from a file

Process model

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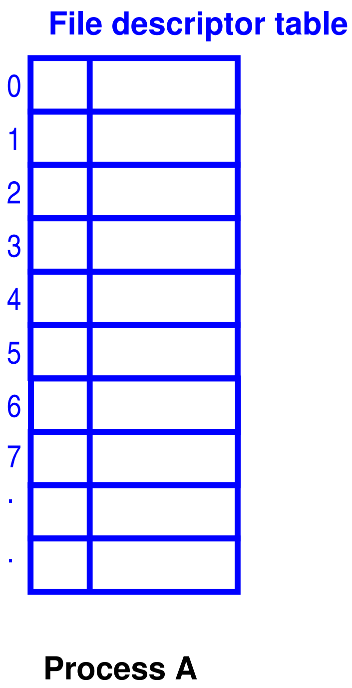
- `fork()` creates (almost) exact copy
  - Much is shared with parent — Copy-On-Write avoids overmuch copying
- `exec()` overwrites memory image from a file
- Allows a process to control what is shared

`fork()` and `exec()`

- A process can clone itself by calling **`fork()`**.
- Most attributes *copied*:
  - Address space (actually shared, marked copy-on-write)
  - current directory, current root
  - File descriptors
  - permissions, etc.
- Some attributes *shared*:
  - Memory segments marked **`MAP_SHARED`**
  - Open files

`fork()` and `exec()`

Files and Processes:



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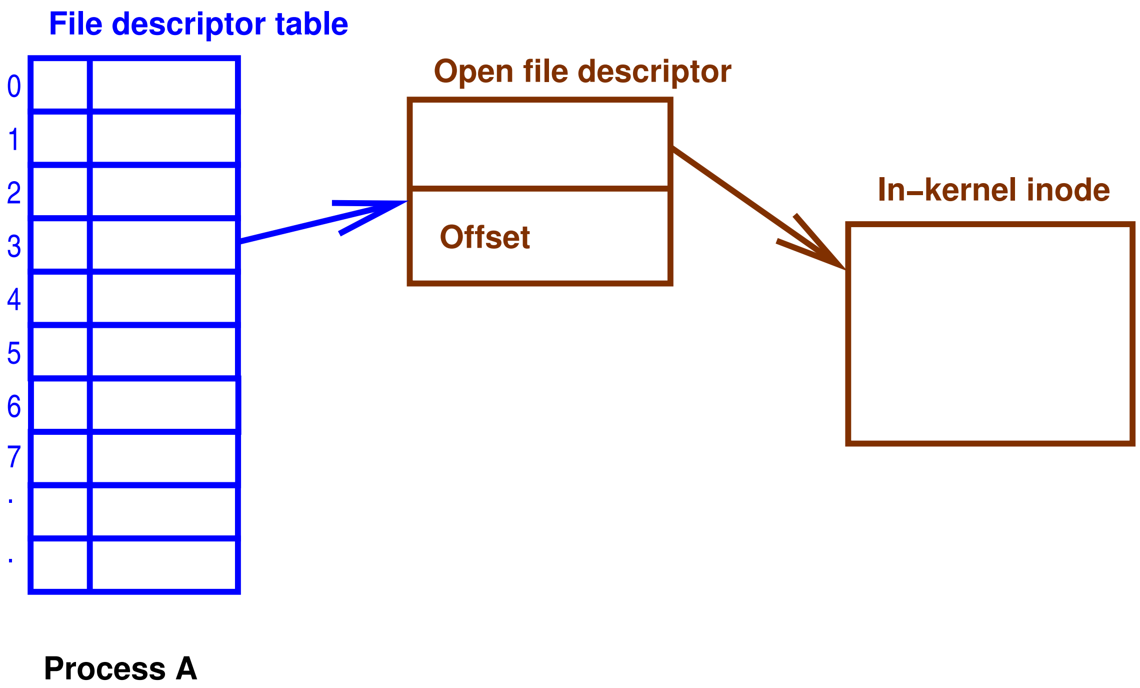

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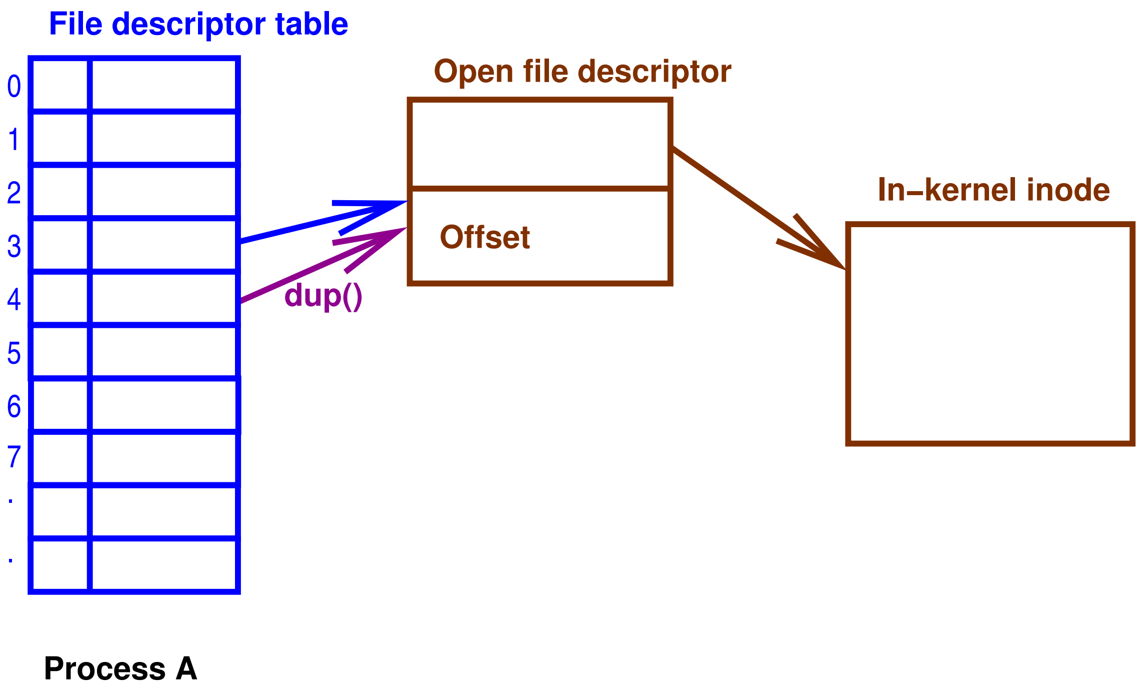

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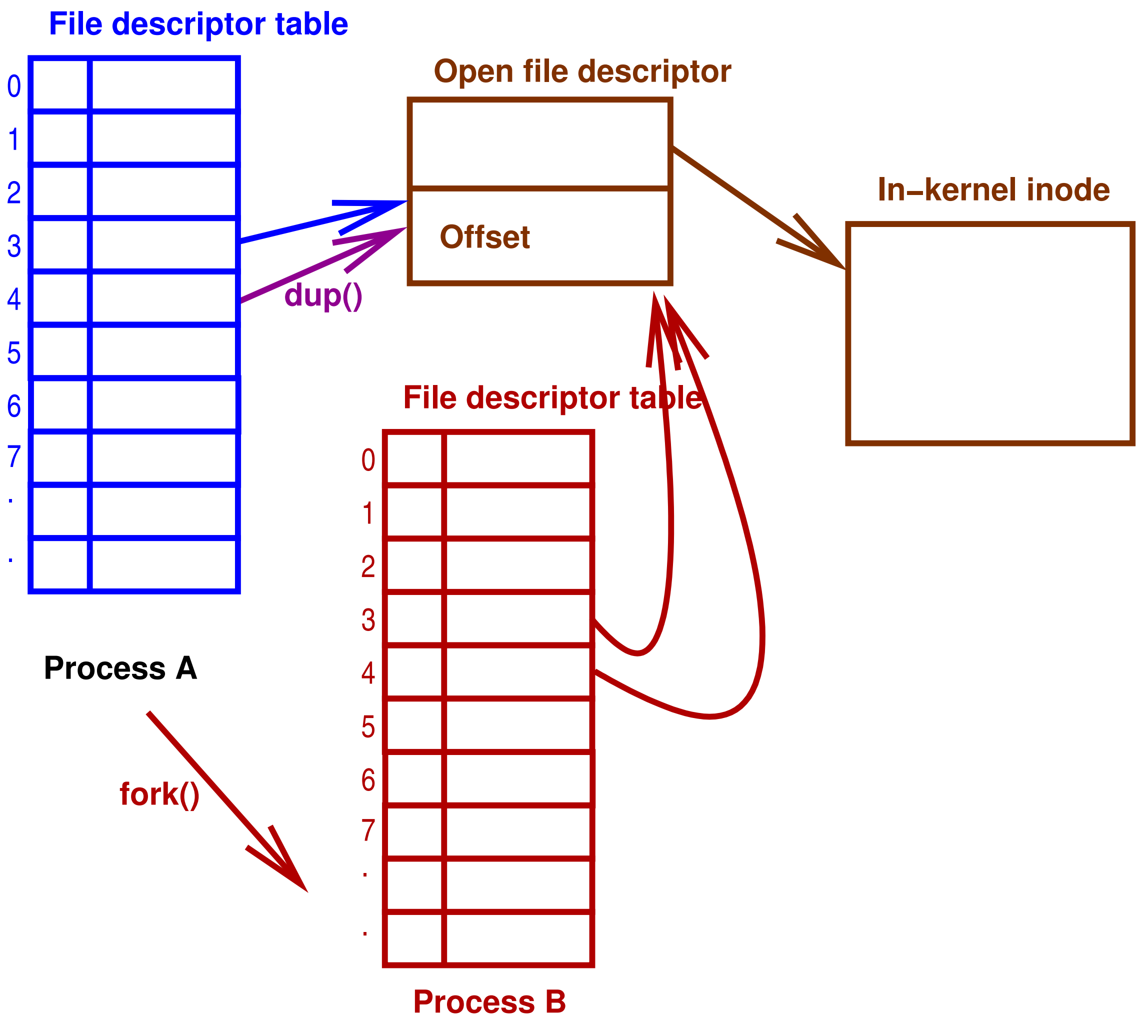


fork() and exec()

```
switch (kidpid = fork()) {
case 0: /* child */
   close(0); close(1); close(2);
   dup(infd); dup(outfd); dup(outfd);
   execve("path/to/prog", argv, envp);
   _exit(EXIT_FAILURE);
case -1:
     /* handle error */
default:
   waitpid(kidpid, &status, 0);
}
```

Standard File Descriptors

0 Standard Input

1 Standard Output

2 Standard Error

➜ Inherited from parent

➜ On login, all are set to *controlling tty*

The problem with `fork()`

- Almost perfect in original system
  - Implemented in a few lines of assembly
  - Alowed re-use of system calls for changing state
  - Fast for segment-style (not paged) MMU

The problem with `fork()`

- Almost perfect in original system
- But:
  - Address spaces now bigger and managed with pages
    - Slow to copy page tables
  - Multi-threading breaks semantics
    - Child no longer an exact copy — only one thread `fork()`ed
    - Much more per-process state, not all inheritable

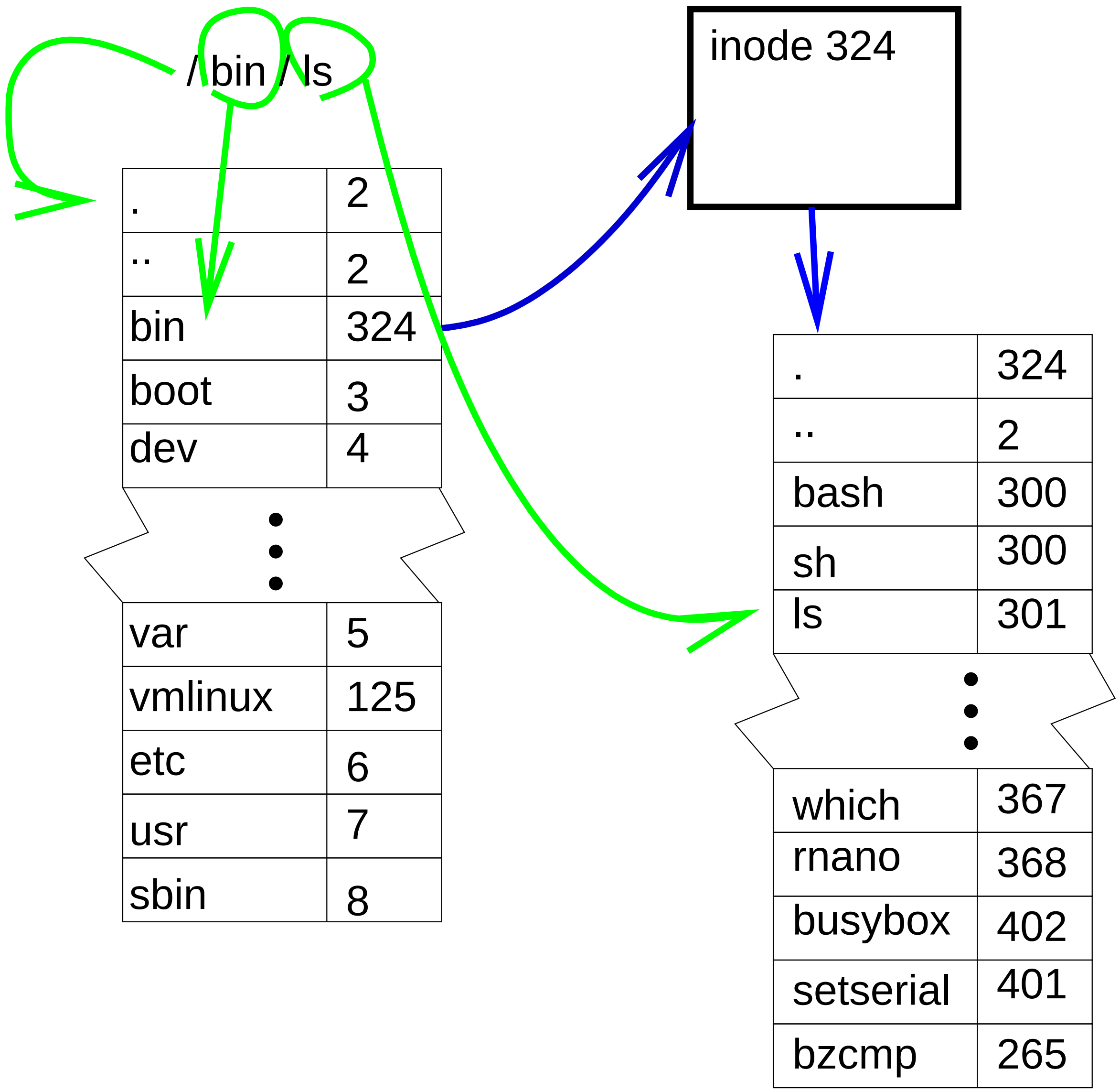
Permissions Model

- Based on logged-in-users
- UID, GID, Other — rwx
- Mainly for File access.

File model

- Separation of names from content.
- ‘regular’ files ‘just bytes’ $\rightarrow$ structure/meaning supplied by userspace
- Devices represented by files.
- Directories map names to index node indices (`inums`)
- Simple permissions model based on who you are.

File model


/ bin / ls
inode 324
. 2
.. 2
bin 324
boot 3
dev 4
var 5
vmlinux 125
etc 6
usr 7
sbin 8
. 324
.. 2
bash 300
sh 300
ls 301
which 367
rnano 368
busybox 402
setserial 401
bzcmp 265

namei

- ➜ translate name $\rightarrow$ inode
- ➜ abstracted per filesystem in VFS layer
- ➜ Can be slow: extensive use of caches to speed it up *dentry cache*
- ➜ hide filesystem and device boundaries
- ➜ walks pathname, translating symbolic links

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- ➜ translate name $\rightarrow$ inode
- ➜ abstracted per filesystem in VFS layer
- ➜ Can be slow: extensive use of caches to speed it up *dentry cache* — becomes SMP bottleneck
- ➜ hide filesystem and device boundaries
- ➜ walks pathname, translating symbolic links

Evolution

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➜ Simplest possible algorithm used at first

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Evolution

KISS:

- ➜ Simplest possible algorithm used at first
  - ➜ Easy to show correctness
  - ➜ Fast to implement
- ➜ As drawbacks and bottlenecks are found, replace with faster/more scalable alternatives

Linux C Dialect

- Extra keywords:
  - Section IDs: `__init`, `__exit`, `__percpu` etc
  - Info Taint annotation `__user`, `__rcu`, `__kernel`, `__iomem`
  - Locking annotations `__acquires(X)`, `__releases(x)`
  - extra typechecking (endian portability) `__bitwise`

Linux C Dialect

- Extra iterators
  - *type_name*`_foreach()`
- Extra O-O accessors
  - `container_of()`
- Macros to register Object initialisers

Linux C Dialect

- Massive use of inline functions
- Quite a big use of CPP macros
- Little `#ifdef` use in code: rely on optimiser to elide dead code.

Internal Abstractions

- ➜ MMU
- ➜ Memory consistency model
- ➜ Device model

Scheduling

Goals:

- dispatch O(1) in number of runnable processes, number of processors
  - good uniprocessor performance
- ‘fair’
- Good interactive response
- topology-aware
- O(log n) for scheduling in number of runnable processes.

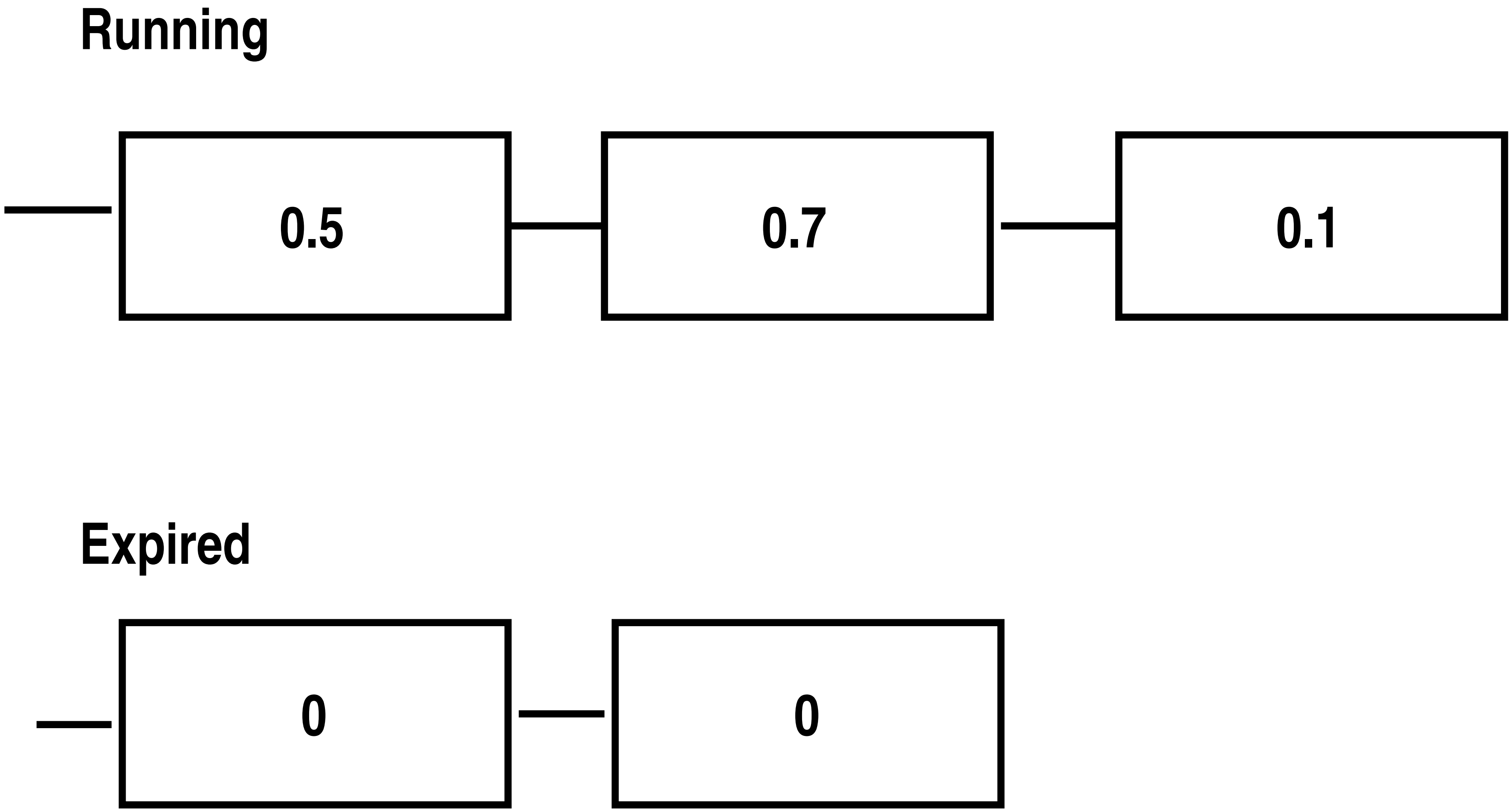
Scheduling

Implementation:

- Changes from time to time.
- Currently ‘CFS’ by Ingo Molnar.

Scheduling

Dual Entitlement Scheduler



Scheduling

CFS:

1. Keep tasks ordered by effective CPU runtime weighted by nice in red-black tree
2. Always run left-most task.

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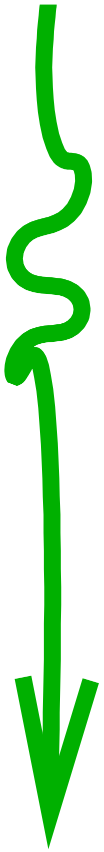
Devil's in the details:

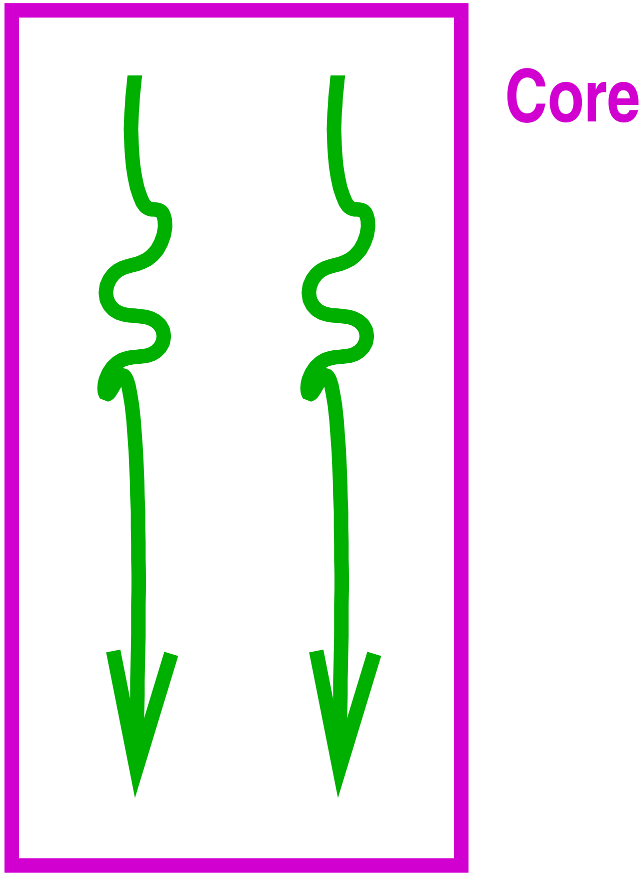
- Avoiding overflow
- Keeping recent history
- multiprocessor locality
- handling too-many threads
- Sleeping tasks
- Group hierarchy

Scheduling



(hyper)Thread

Scheduling



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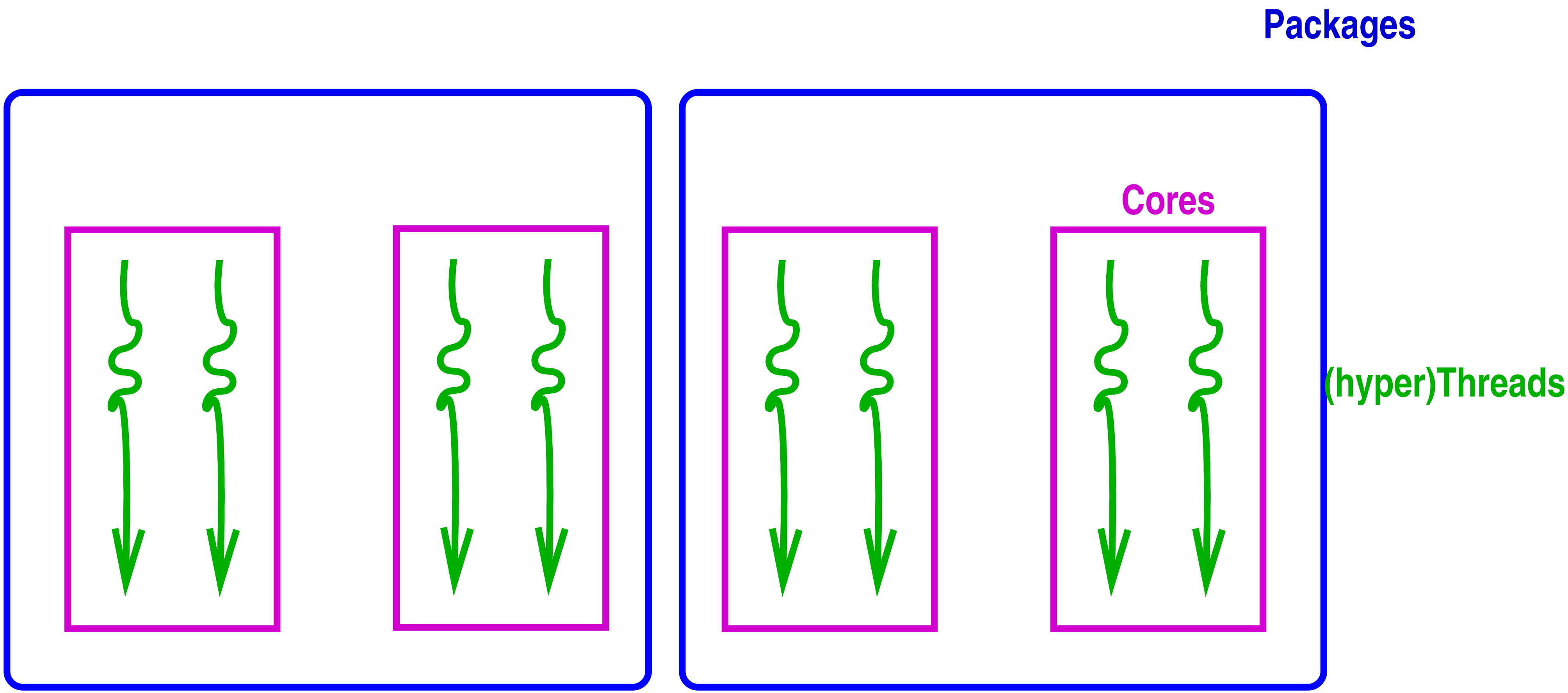

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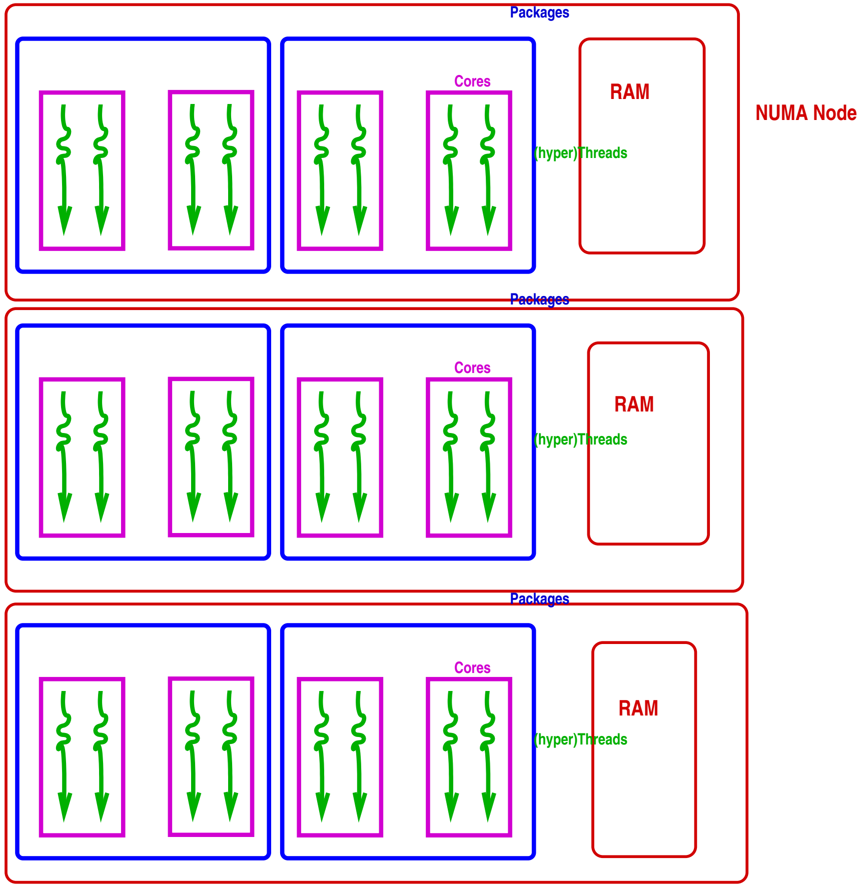
Packages
Cores
RAM
NUMA Node
(hyper)Threads
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- Best to reschedule on same processor (don't move cache footprint, keep memory close)

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Locality Issues:

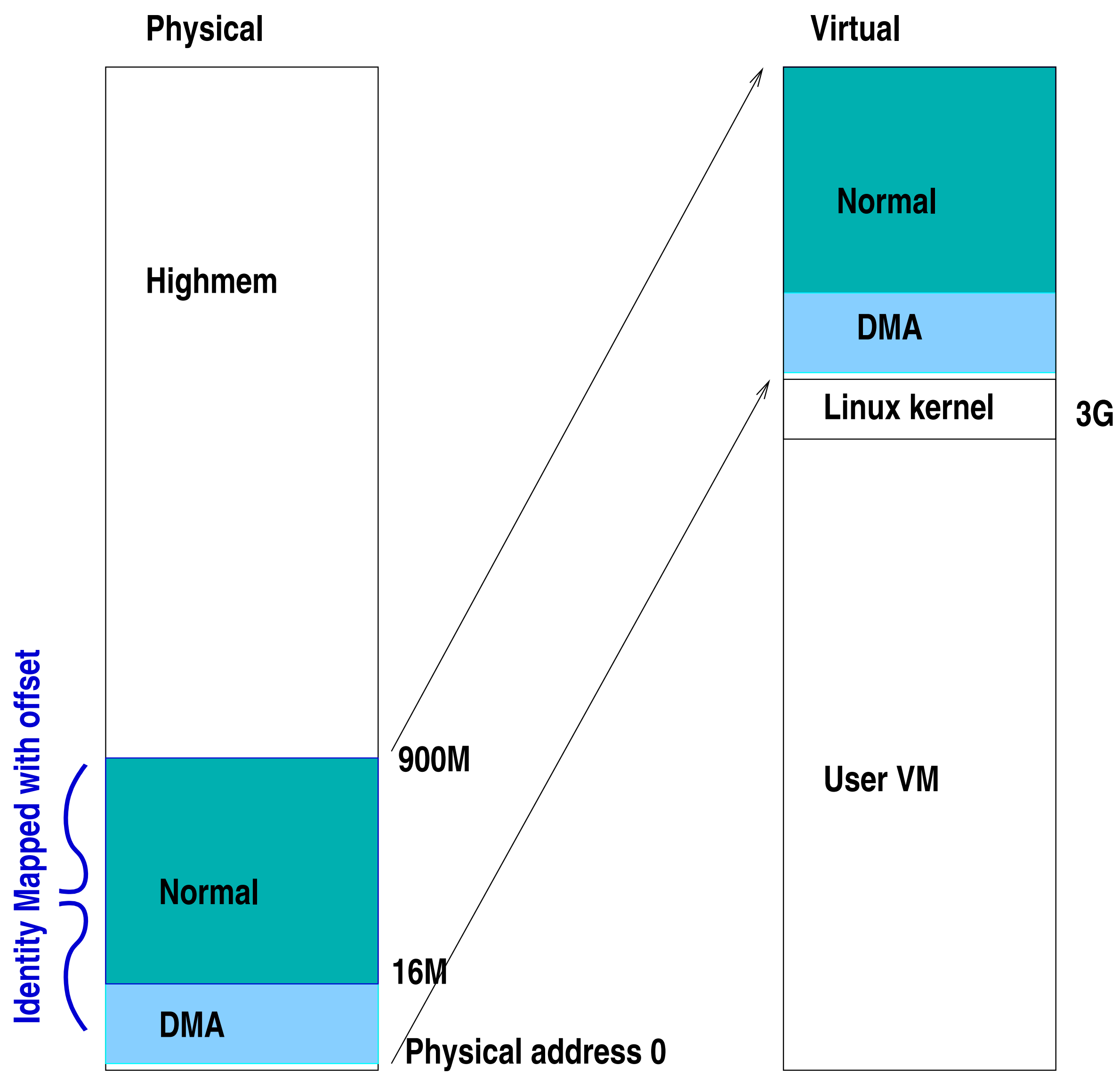
- Best to reschedule on same processor (don't move cache footprint, keep memory close)
  - Otherwise schedule on a 'nearby' processor
- Try to keep whole sockets idle (can power them off)
- Somehow identify cooperating threads, co-schedule 'close by'?

Scheduling

- One queue per processor (or hyperthread)
- Processors in hierarchical ‘domains’
- Load balancing per-domain, bottom up
- Aims to keep whole domains idle if possible (power savings)

Memory Management

Memory in *zones*



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  - `__pa()` and `__va()` convert physical to virtual for these

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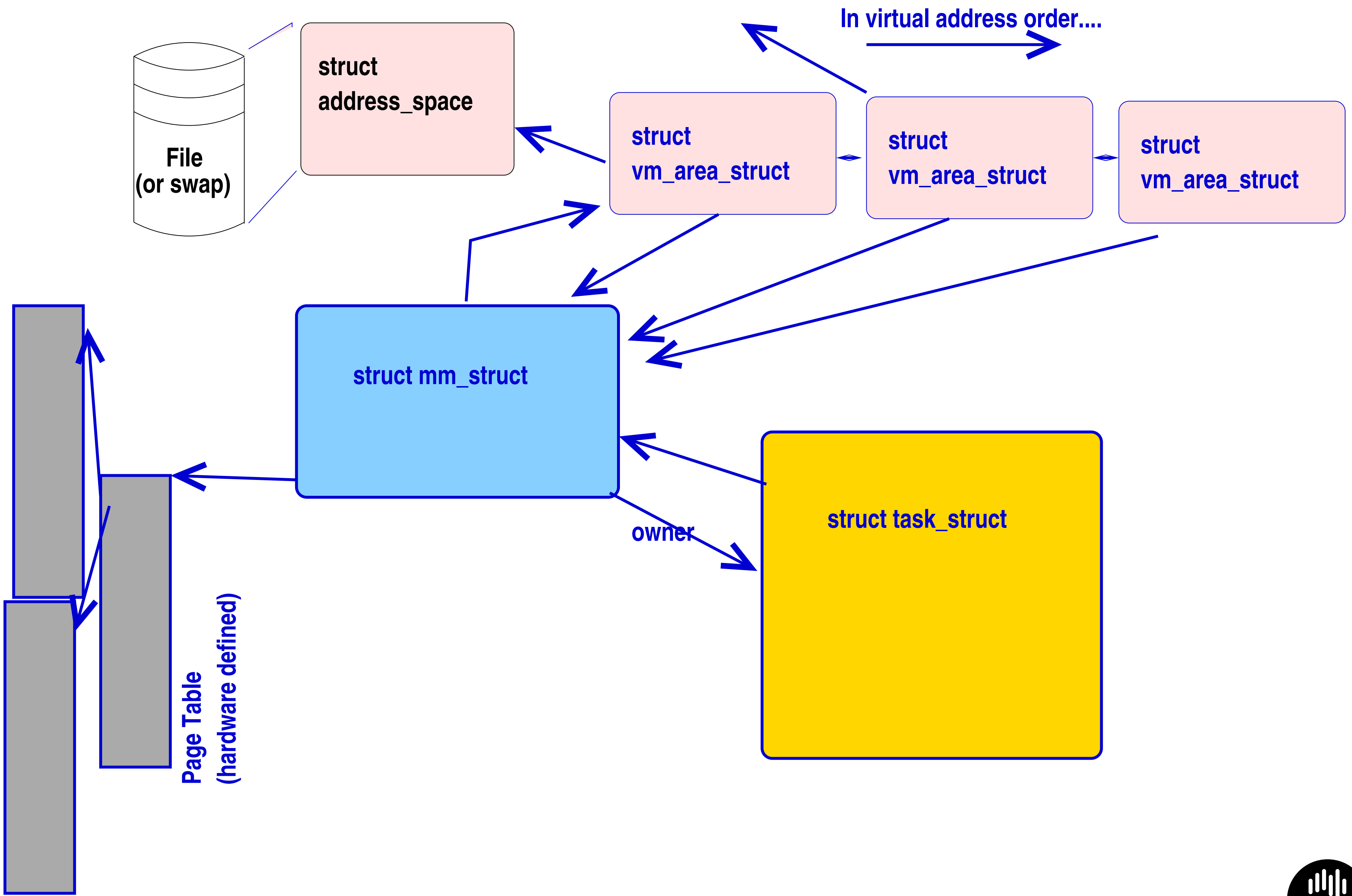
- More memory $\rightarrow \Delta$ kernel refer to memory by `struct page`

Memory Management

`struct page`:

- Every frame has a `struct page` (up to 10 words)
- Track:
  - flags
  - backing address space
  - offset within mapping *or* freelist pointer
  - Reference counts
  - Kernel virtual address (if mapped)

Memory Management



Memory Management

Address Space:

- Misnamed: means collection of pages mapped from the same object
- Tracks inode mapped from, radix tree of pages in mapping
- Has ops (from file system or swap manager) to:

dirty mark a page as dirty

readpages populate frames from backing store

writepages Clean pages — make backing store the same as in-memory copy

migratepage Move pages between NUMA nodes

Others. . . And other housekeeping

Page fault time

- Special case in-kernel faults
- Find the VMA for the address
  - segfault if not found (unmapped area)
- If it's a stack, extend it.
- Otherwise:
  1. Check permissions, SIG_SEGV if bad
  2. Call **`handle_mm_fault()`**:
     - walk page table to find entry (populate higher levels if nec. until leaf found)
     - call **`handle_pte_fault()`**

Page fault time

`handle_pte_fault()`: Depending on PTE status, can

- provide an anonymous page
- do copy-on-write processing
- reinstantiate PTE from page cache
- initiate a read from backing store.

and if necessary flushes the TLB.

Driver Interface

Three kinds of device:

1. Platform device
2. enumerable-bus device
3. Non-enumerable-bus device

Driver Interface

Enumerable buses:

```
static DEFINE_PCI_DEVICE_TABLE(cp_pci_tbl) = {
  { PCI_DEVICE(PCI_VENDOR_ID_REALTEK,
        PCI_DEVICE_ID_REALTEK_8139), },
  { PCI_DEVICE(PCI_VENDOR_ID_TTTECH,
        PCI_DEVICE_ID_TTTECH_MC322), },
  { },
};
MODULE_DEVICE_TABLE(pci, cp_pci_tbl);
```

Driver Interface

Driver interface:

`init` called to register driver

`exit` called to deregister driver, at module unload time

`probe()` called when bus-id matches; returns 0 if driver claims device

open, close, etc as necessary for driver class

Driver Interface

Platform Devices (old way):

```
static struct platform_device nslu2_uart = {
.name = "serial8250",
.id = PLAT8250_DEV_PLATFORM,
.dev.platform_data = nslu2_uart_data,
.num_resources = 2,
.resource = nslu2_uart_resources,
};
```

Driver Interface

non-enumerable buses: Treat like platform devices

Device Tree

- Describe board+peripherals

Device Tree

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  - replaces ACPI on embedded systems

Device Tree

- Describe board+peripherals
  - replaces ACPI on embedded systems
- Names in device tree trigger driver instantiation

Device Tree

```
uart_A: serial@84c0 {
    compatible = "amlogic,meson6-uart", "amlogic,me
    reg = <0x84c0 0x18>;
    interrupts = <GIC_SPI 26 IRQ_TYPE_EDGE_RISING>;
    status = "ok";
};
```

Containers

- *Namespace* isolation

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- Plus Memory and CPU isolation

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In hierarchy of control groups

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- *Namespace* isolation
- Plus Memory and CPU isolation
- Plus other resources

In hierarchy of control groups

Used to implement, e.g., **`Docker`**

Summary

- I’ve told you status today

Summary

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  - Next week it may be different

Summary

- I’ve told you status today
  - Next week it may be different
- I’ve simplified a lot. There are many hairy details

Scalability

The Multiprocessor Effect:

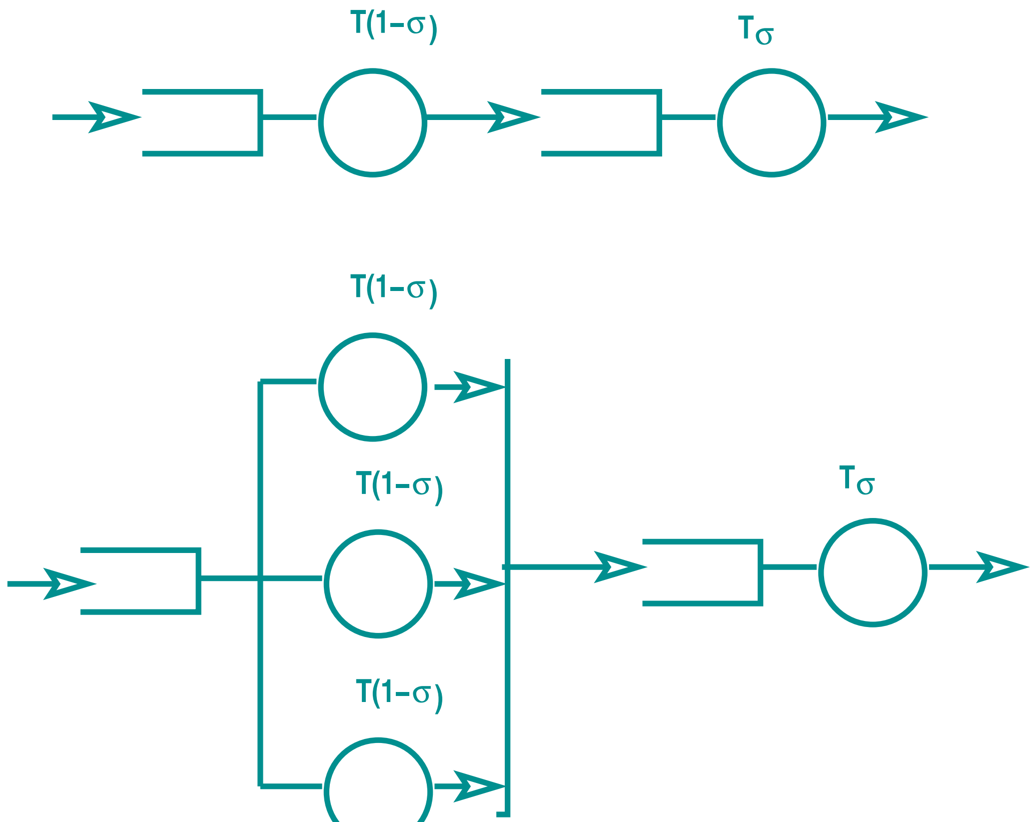
- Some fraction of the system's cycles are not available for application work:
  - Operating System Code Paths
  - Inter-Cache Coherency traffic
  - Memory Bus contention
  - Lock synchronisation
  - I/O serialisation

Scalability

Amdahl's law:

If a process can be split such that σ of the running time cannot be sped up, but the rest is sped up by running on p processors, then overall speedup is

$$\frac{p}{1 + \sigma(p-1)}$$



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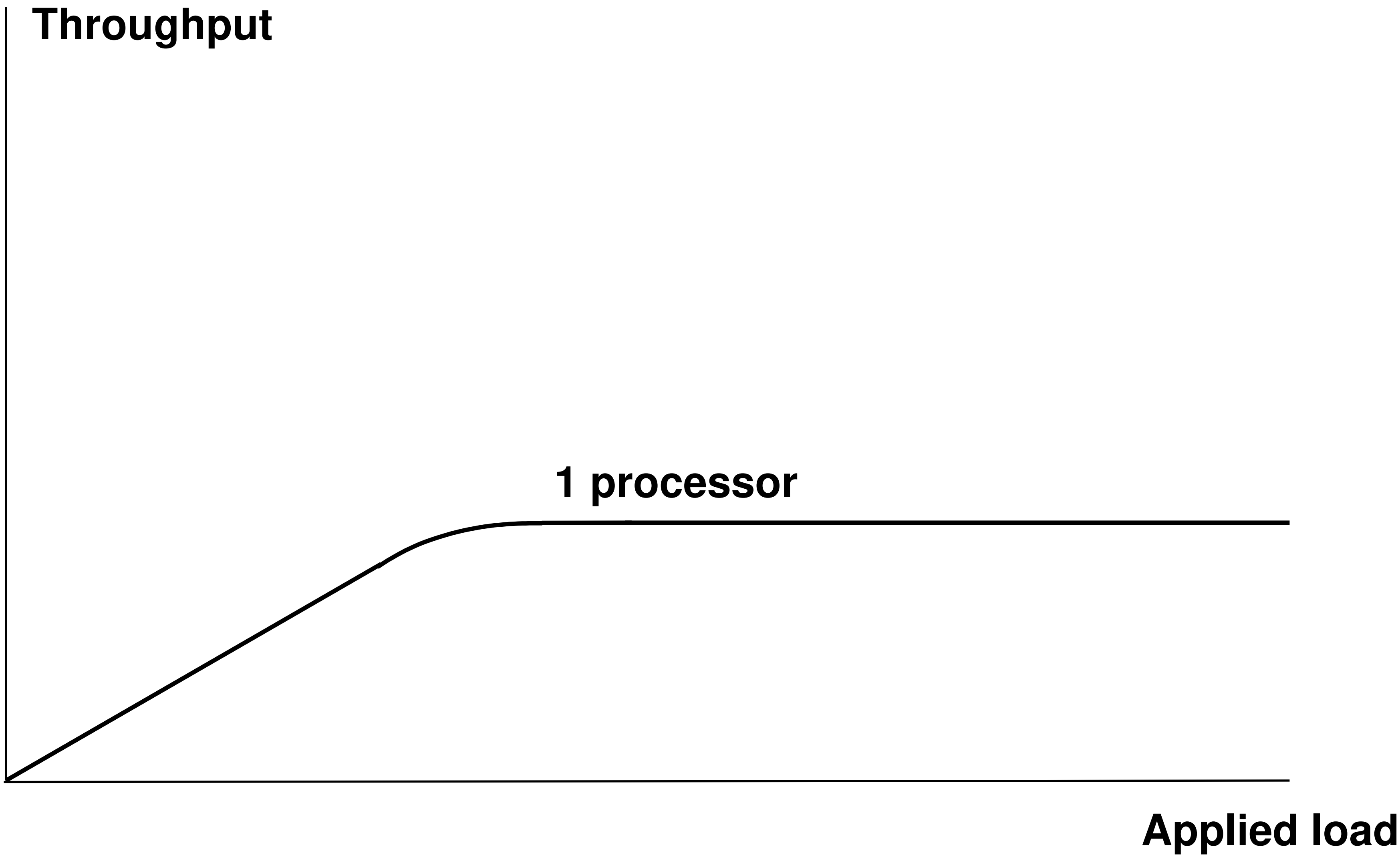

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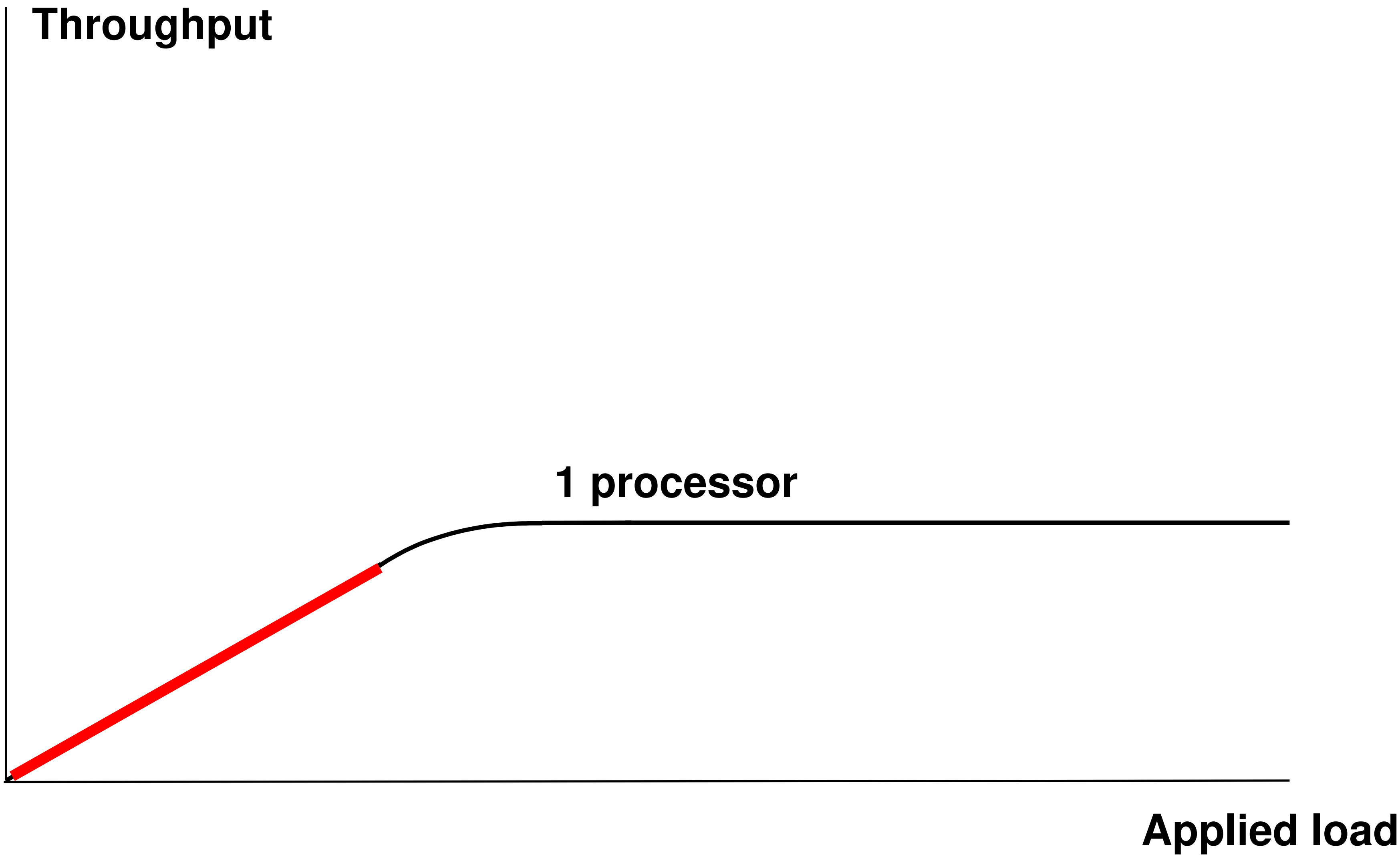

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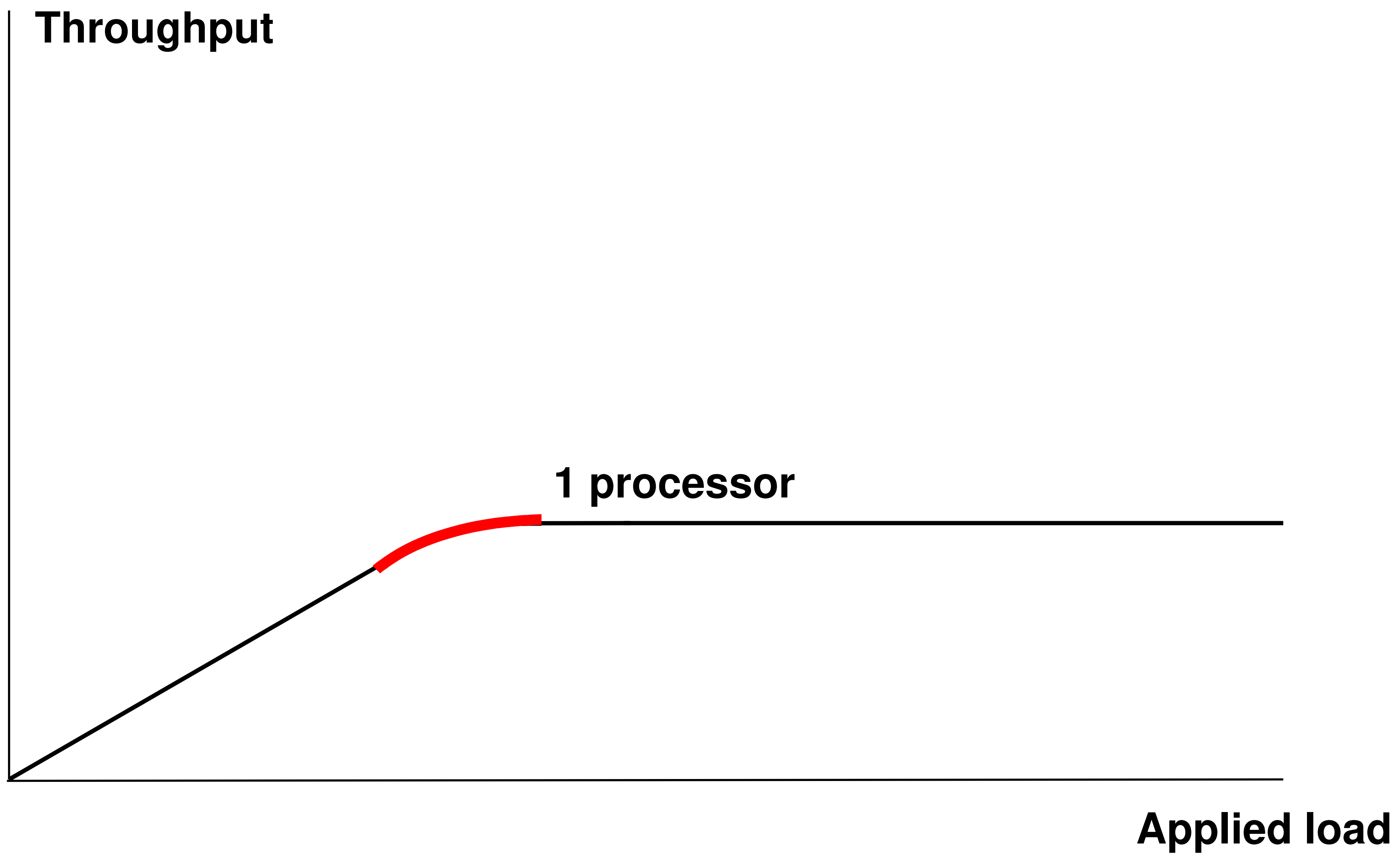

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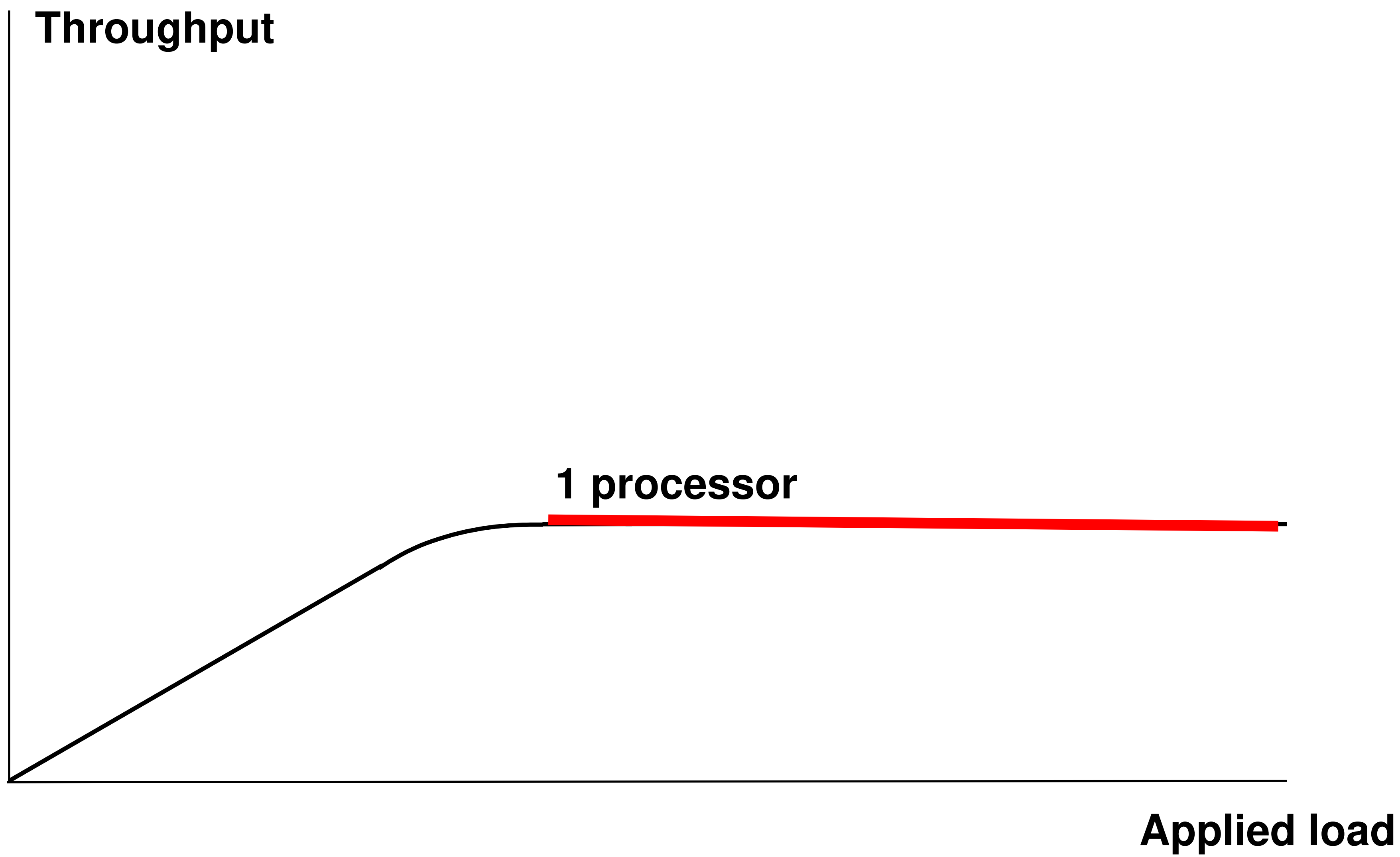

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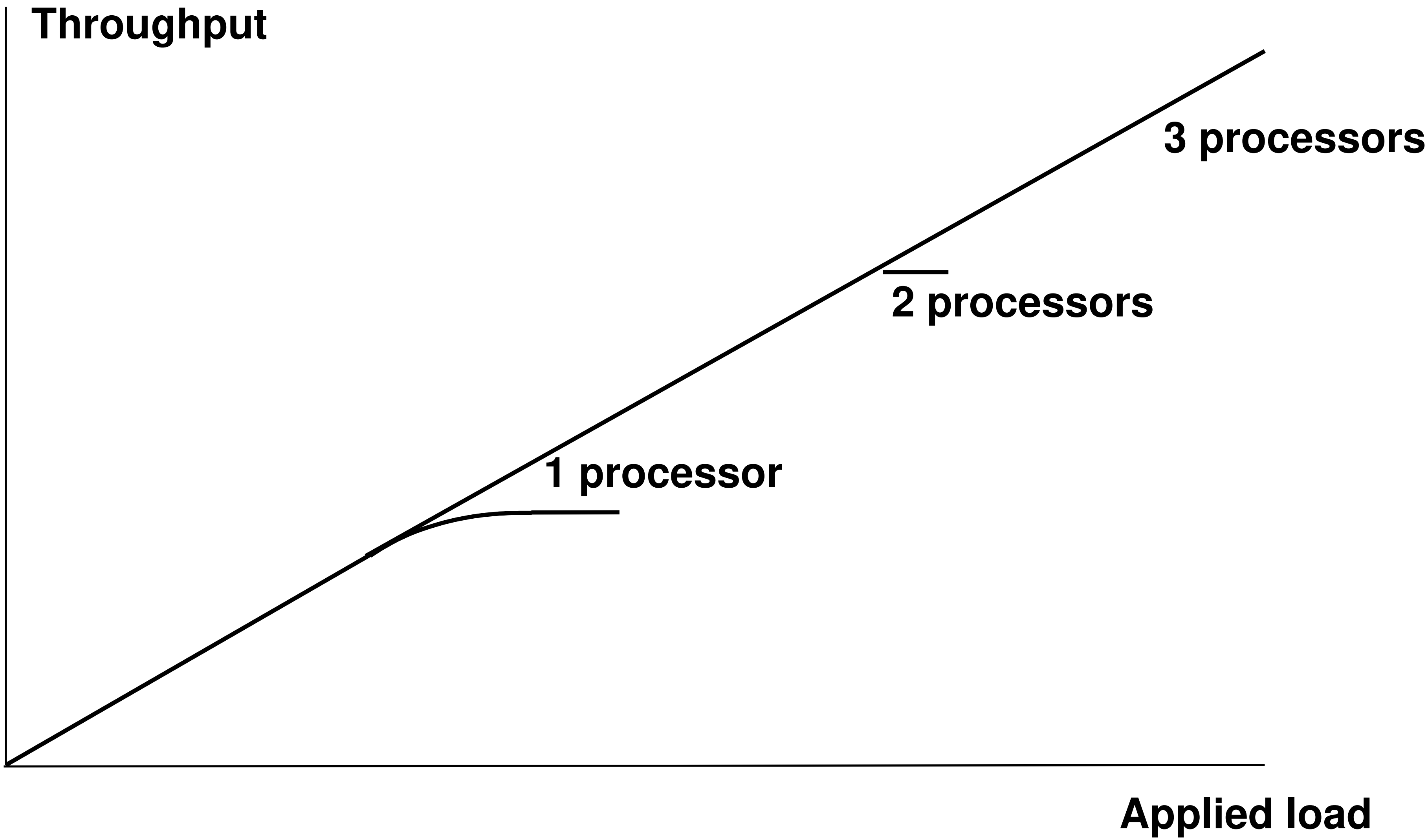

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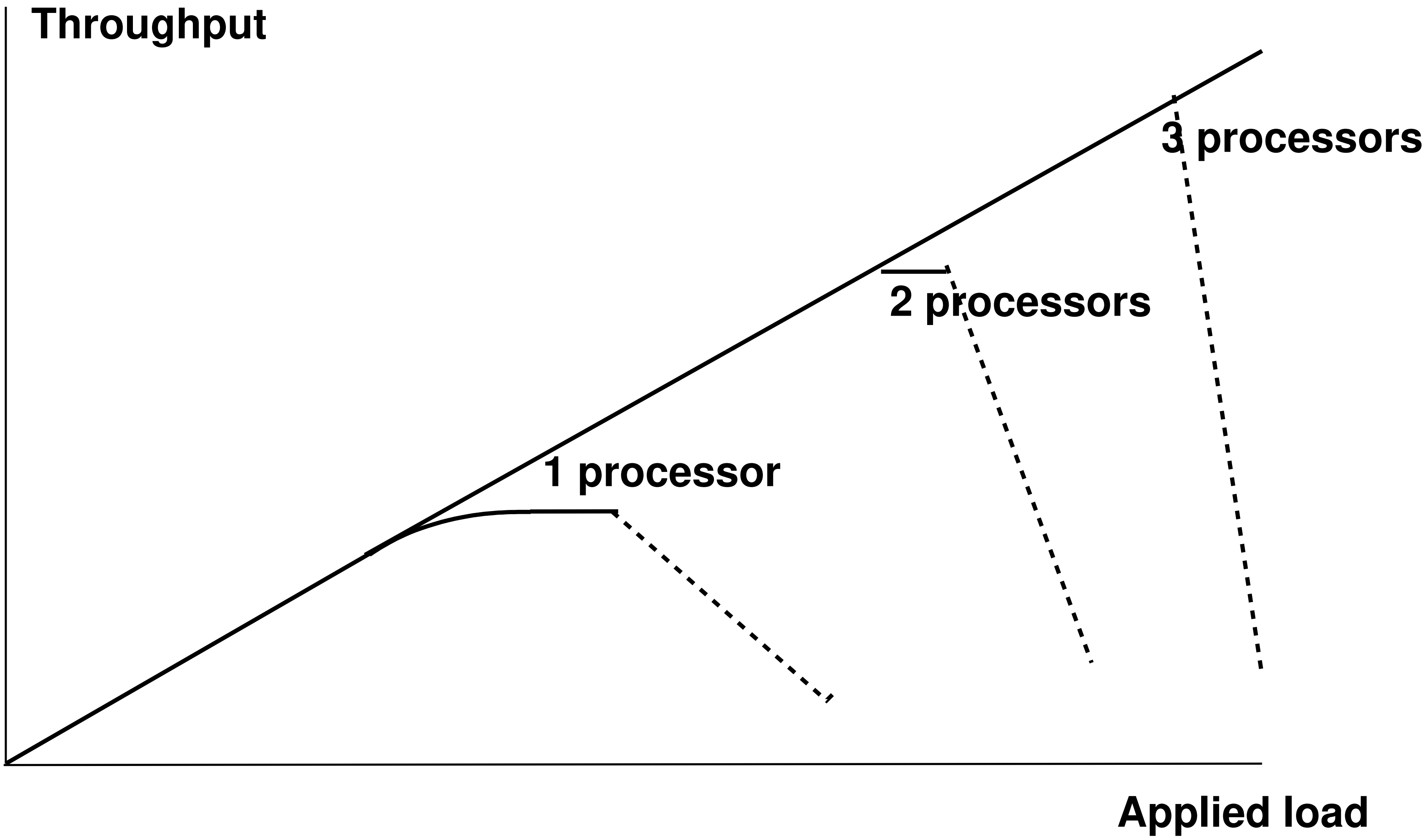

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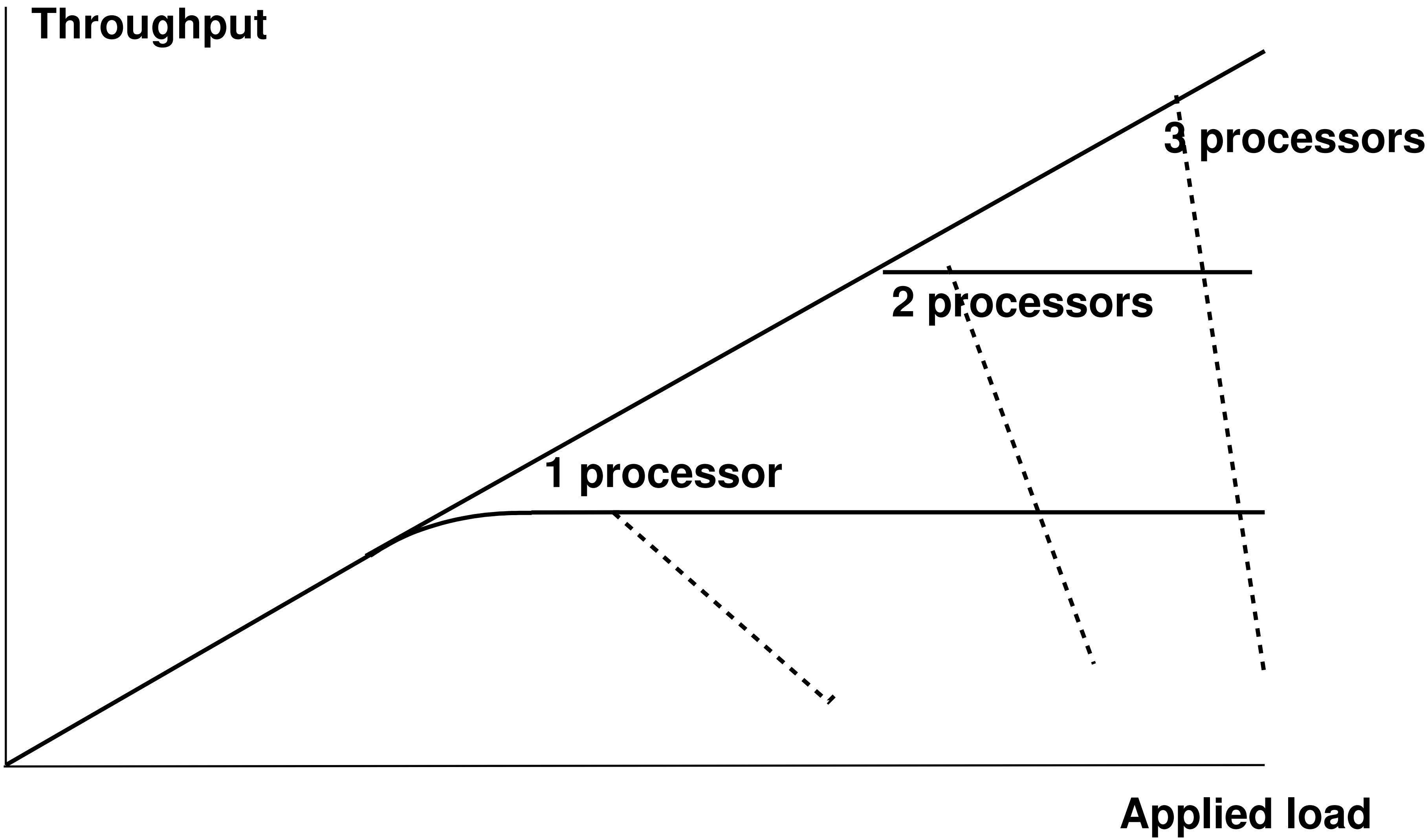

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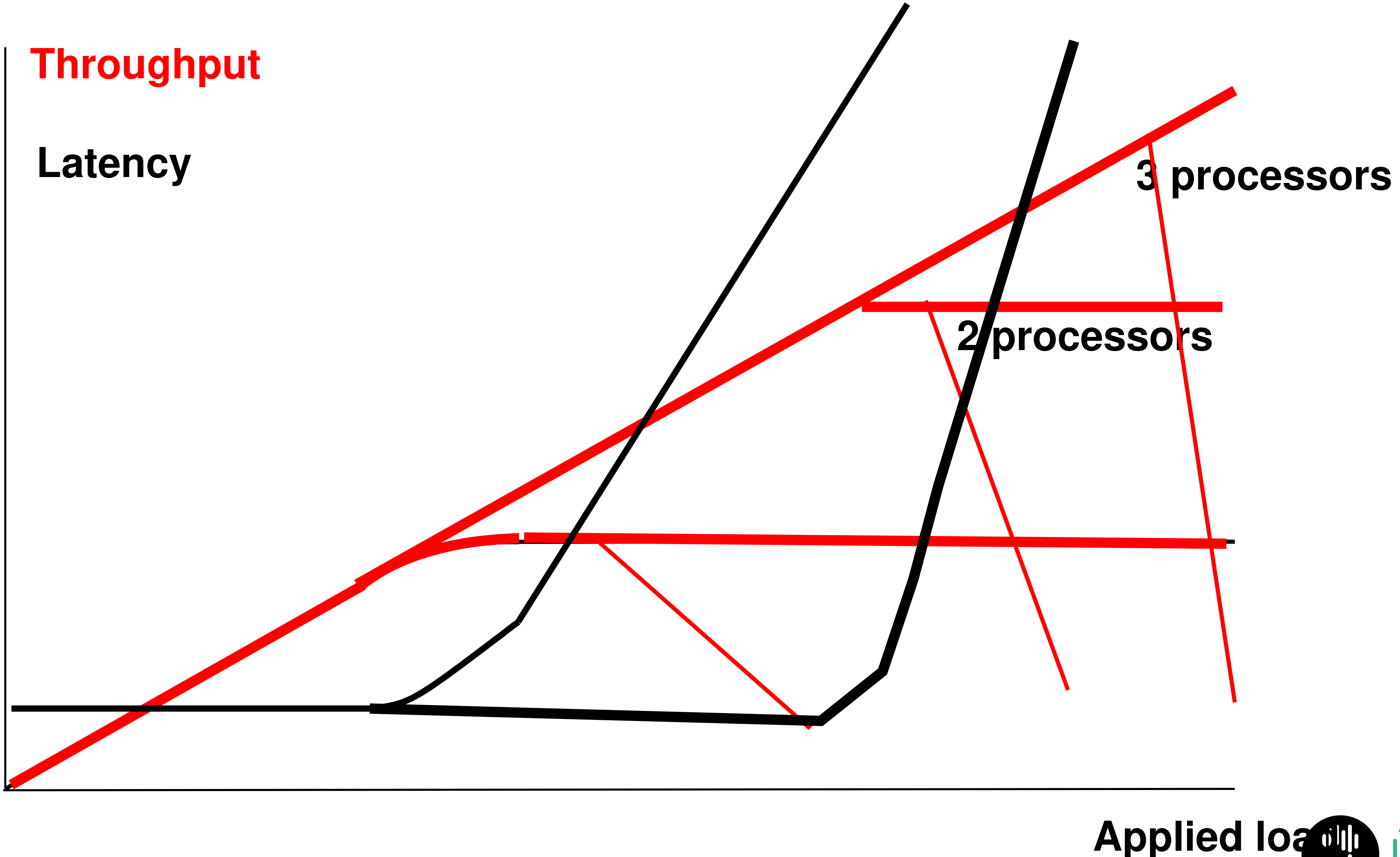


Scalability

Gunther's law:

$$C(N) = \frac{N}{1 + \alpha(N-1) + \beta N(N-1)}$$

where:

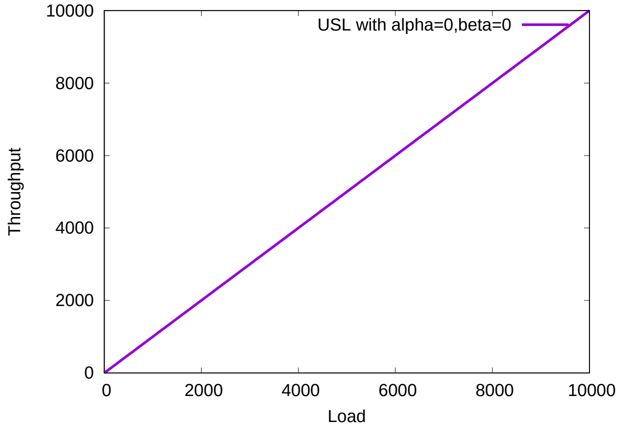
N is demand

α is the amount of serialisation: represents Amdahl's law

β is the coherency delay in the system.

C is Capacity or Throughput

Scalability



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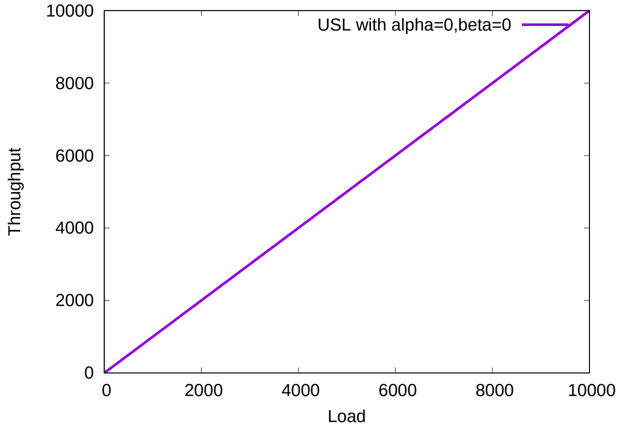

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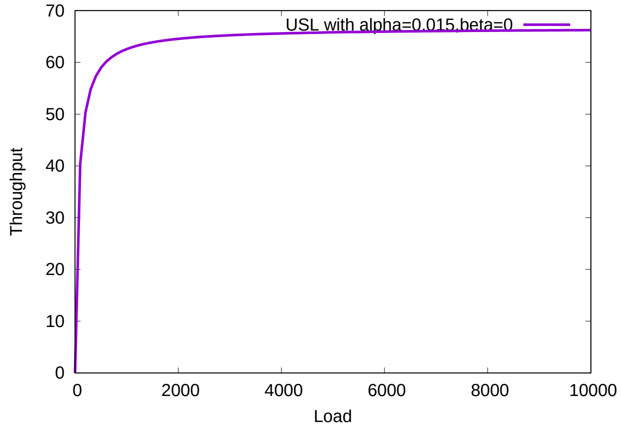

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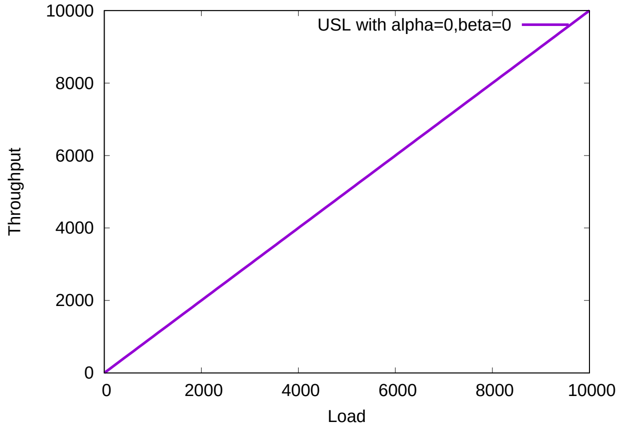

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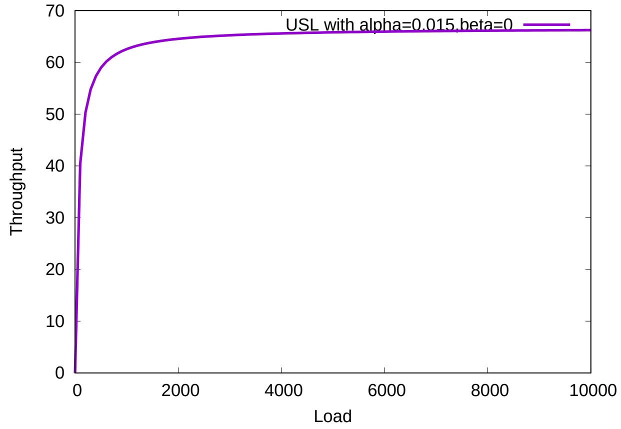

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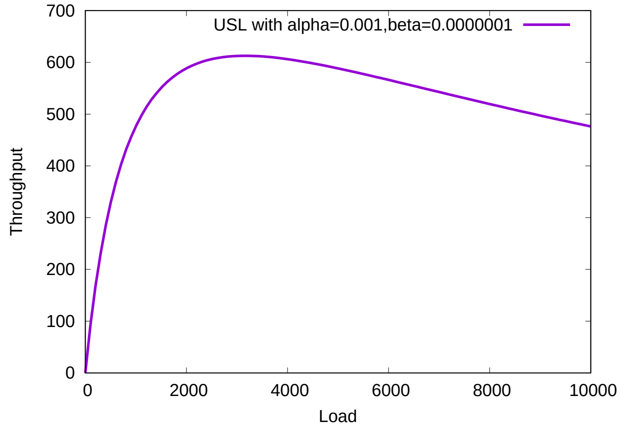

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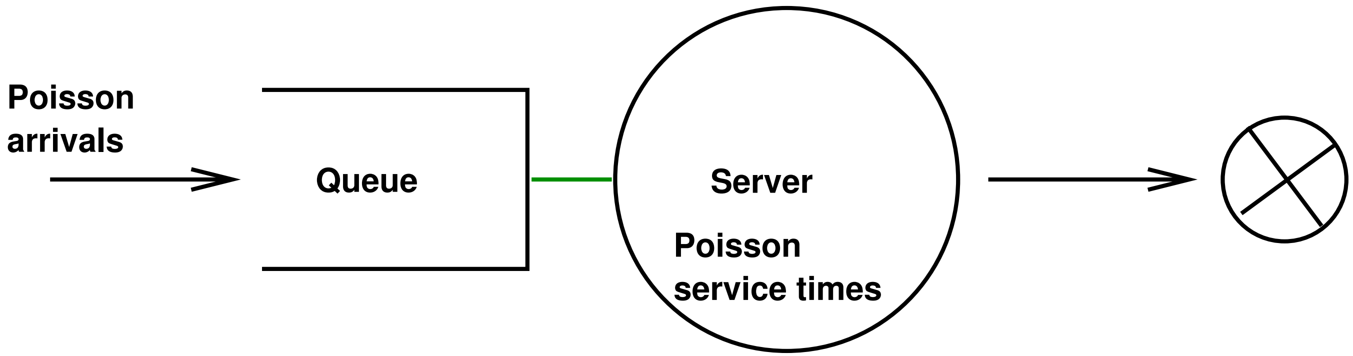
Scalability

Queueing Models:



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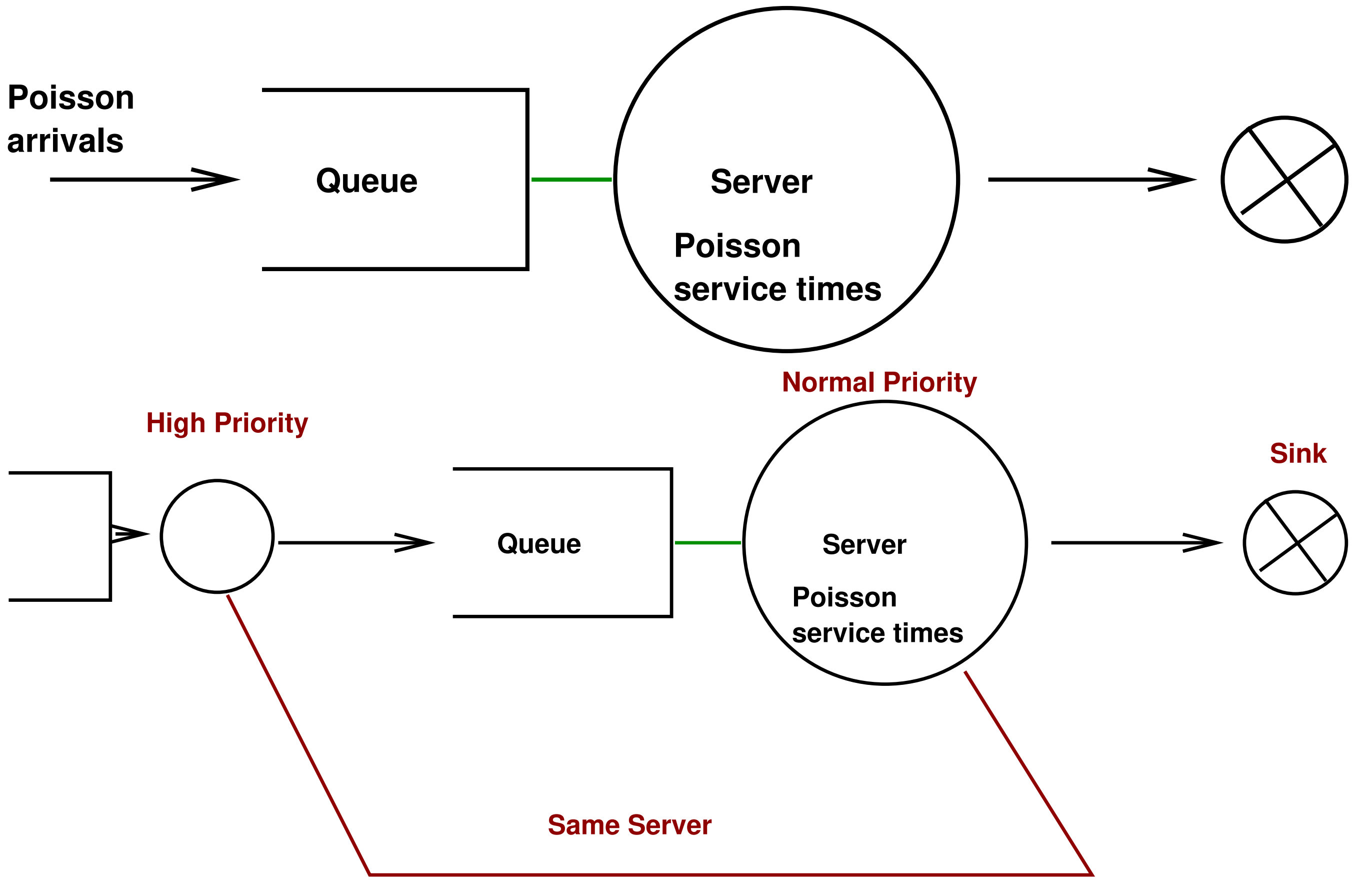
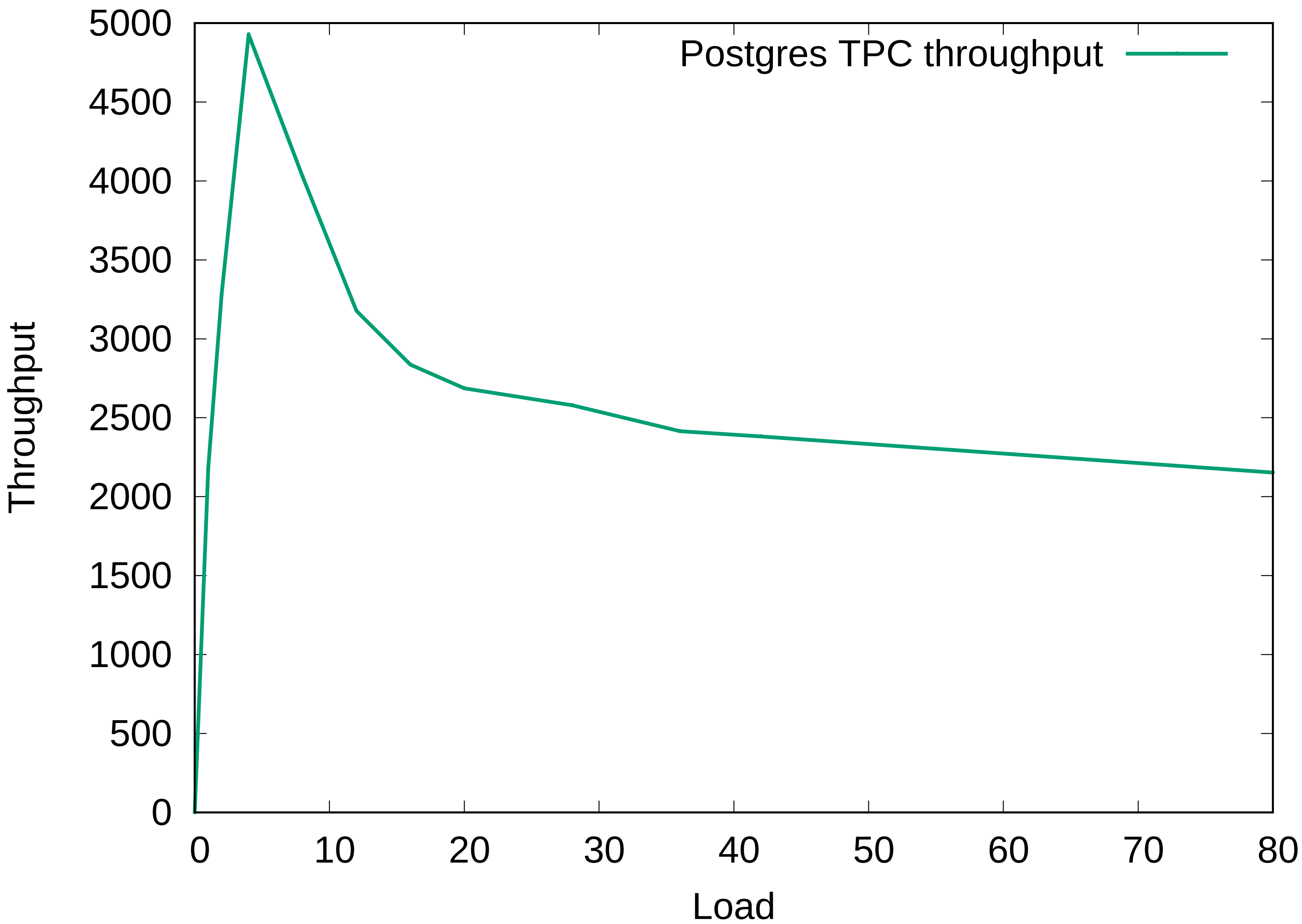


Scalability

Real examples:



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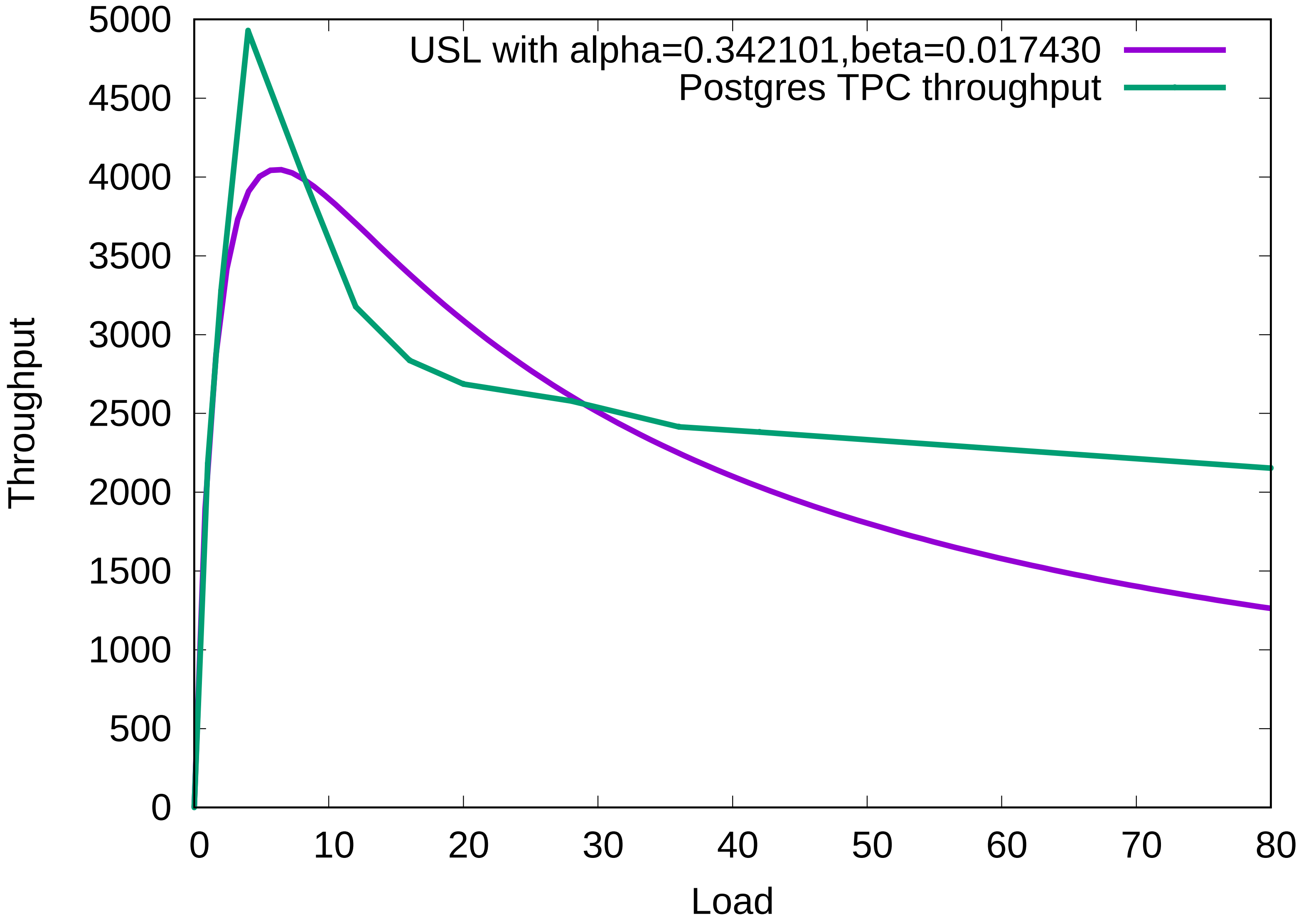

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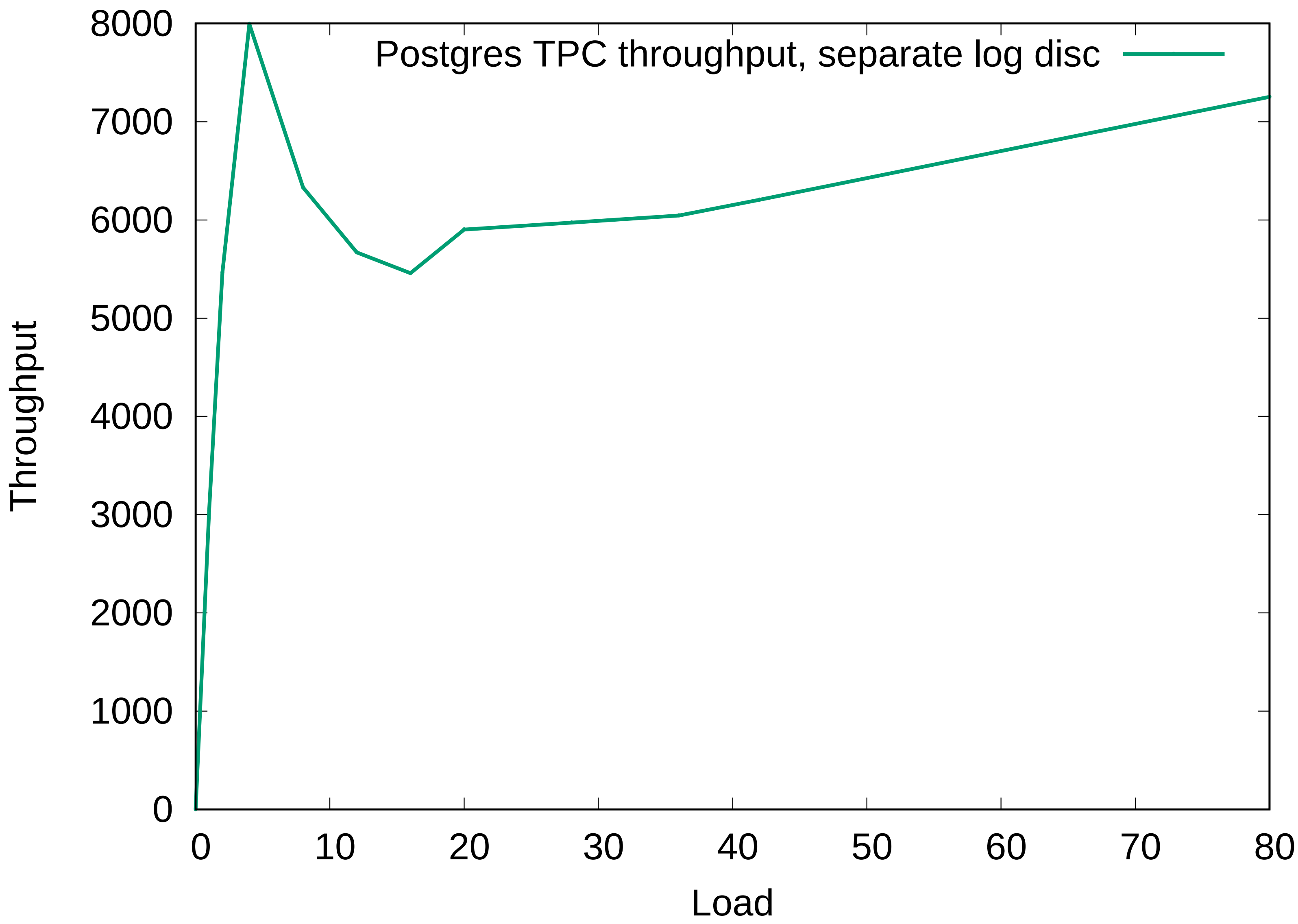
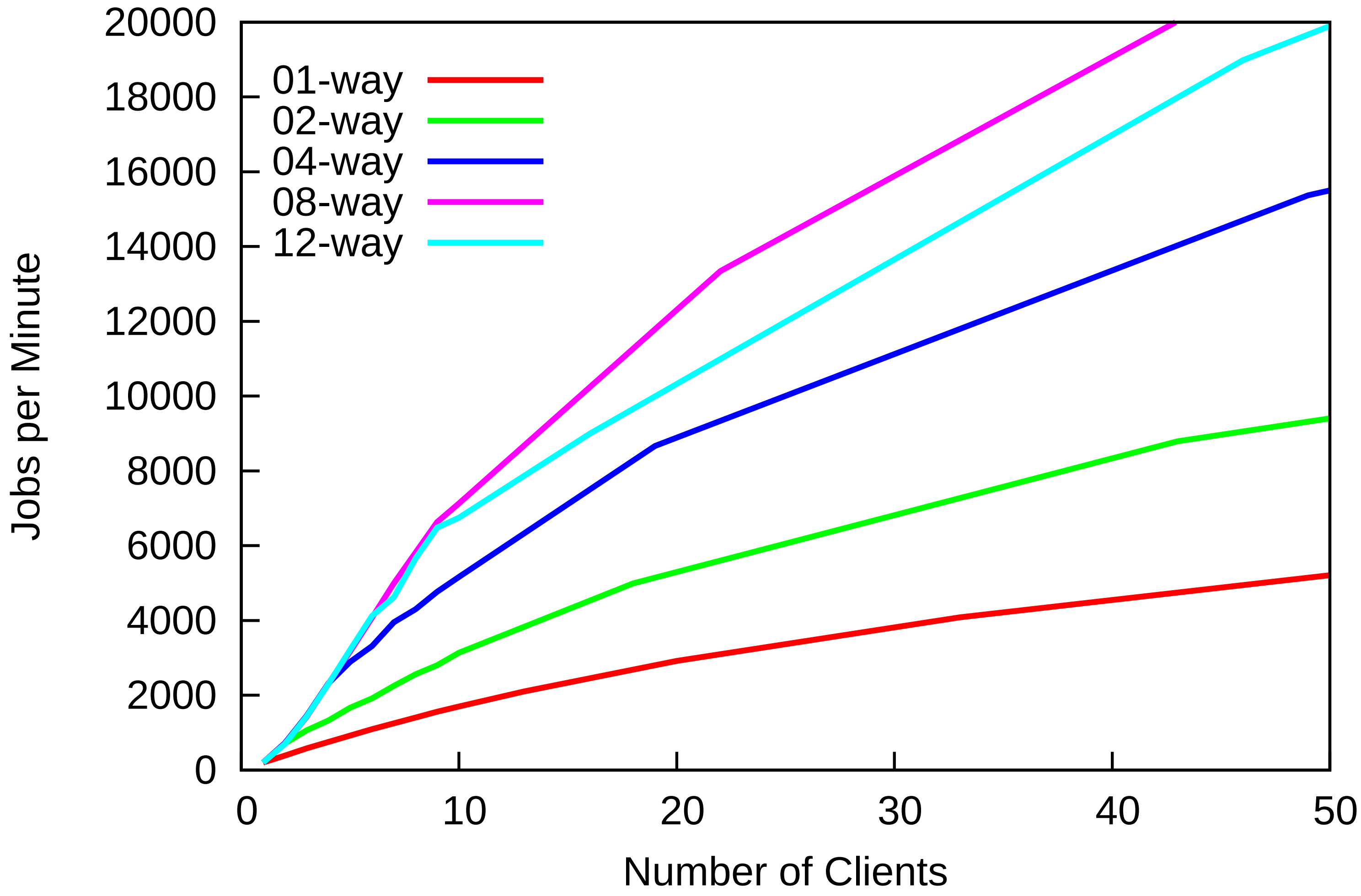


Scalability

Another example:



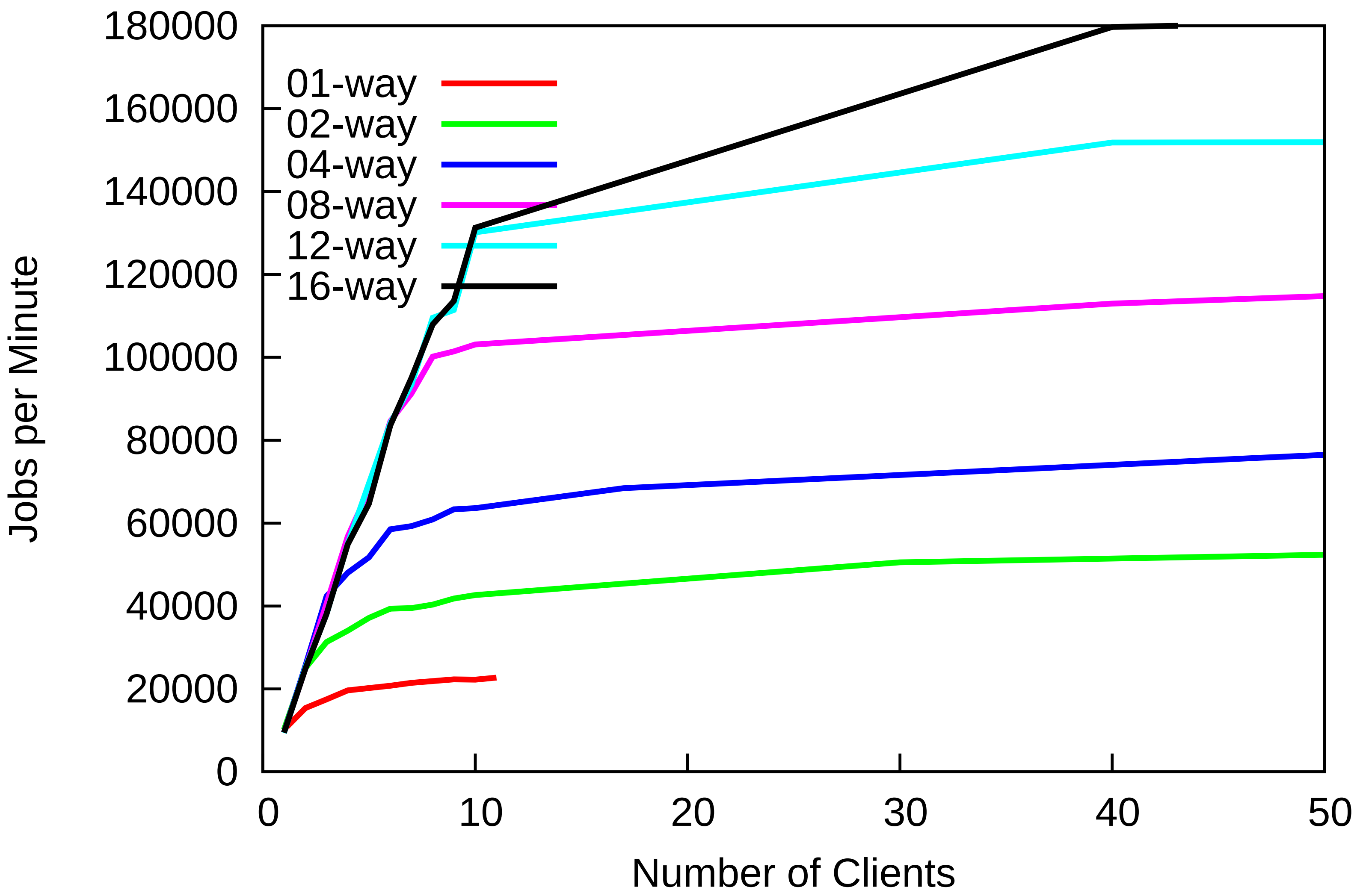
Scalability

```
SPINLOCKS          HOLD            WAIT

UTIL    CON    MEAN( MAX )    MEAN( MAX )(% CPU)      TOTAL NOWAIT SPIN RJECT   NAME

72.3% 13.1% 0.5us(9.5us)    29us( 20ms)(42.5%)   50542055 86.9% 13.1%   0%   find_lock_page+0x30

0.01% 85.3% 1.7us(6.2us)    46us(4016us)(0.01%)      1113 14.7% 85.3%   0%   find_lock_page+0x130
```

Scalability

```
struct page *find_lock_page(struct address_space *mapping,
                                 unsigned long offset)
{
        struct page *page;
        spin_lock_irq(&mapping->tree_lock);
repeat:
        page = radix_tree_lookup(&mapping>page_tree, offset);
        if (page) {
                page_cache_get(page);
                if (TestSetPageLocked(page)) {
                        spin_unlock_irq(&mapping->tree_lock);
                        lock_page(page);
                        spin_lock_irq(&mapping->tree_lock);

                                                      ...
```

Scalability



Tackling scalability problems

- Find the bottleneck

Tackling scalability problems

- Find the bottleneck
  - not always easy

Tackling scalability problems

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- Experiment with different algorithms, parameters

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Doing without locks

Avoiding Serialisation:

- *Lock-free* algorithms
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Avoiding Serialisation:

- *Lock-free* algorithms
- Allow safe concurrent access *without excessive serialisation*
- Many techniques. We cover:
  - Sequence locks
  - Read-Copy-Update (RCU)

Doing without locks

Sequence locks:

- Readers don't lock
- Writers serialised.

Doing without locks

Reader:

```
volatile seq;
do {
  do {
    lastseq = seq;
  } while (lastseq & 1);
  rmb();
  reader body ....
} while (lastseq != seq);
```

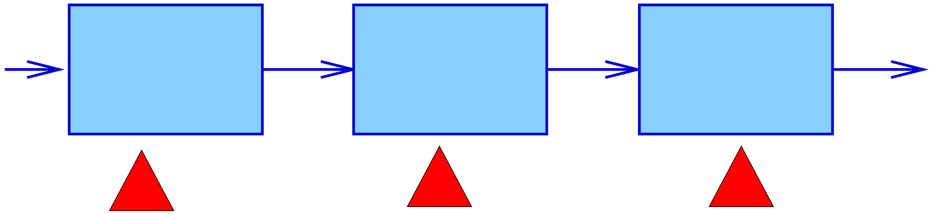
Writer:

```
spinlock(&lck);
seq++; wmb()
writer body ...
wmb(); seq++;
spinunlock(&lck);
```

Doing without locks

RCU: McKenney (2004), McKenney et al. (2002)

1.



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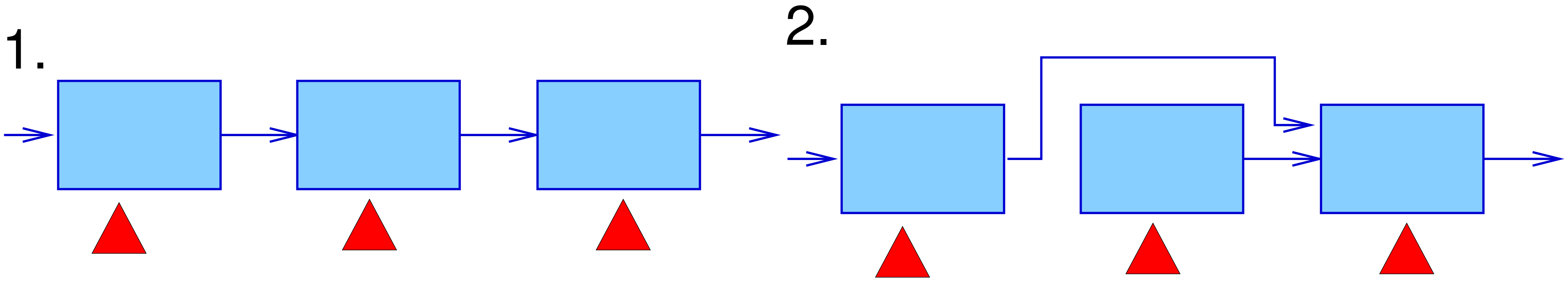

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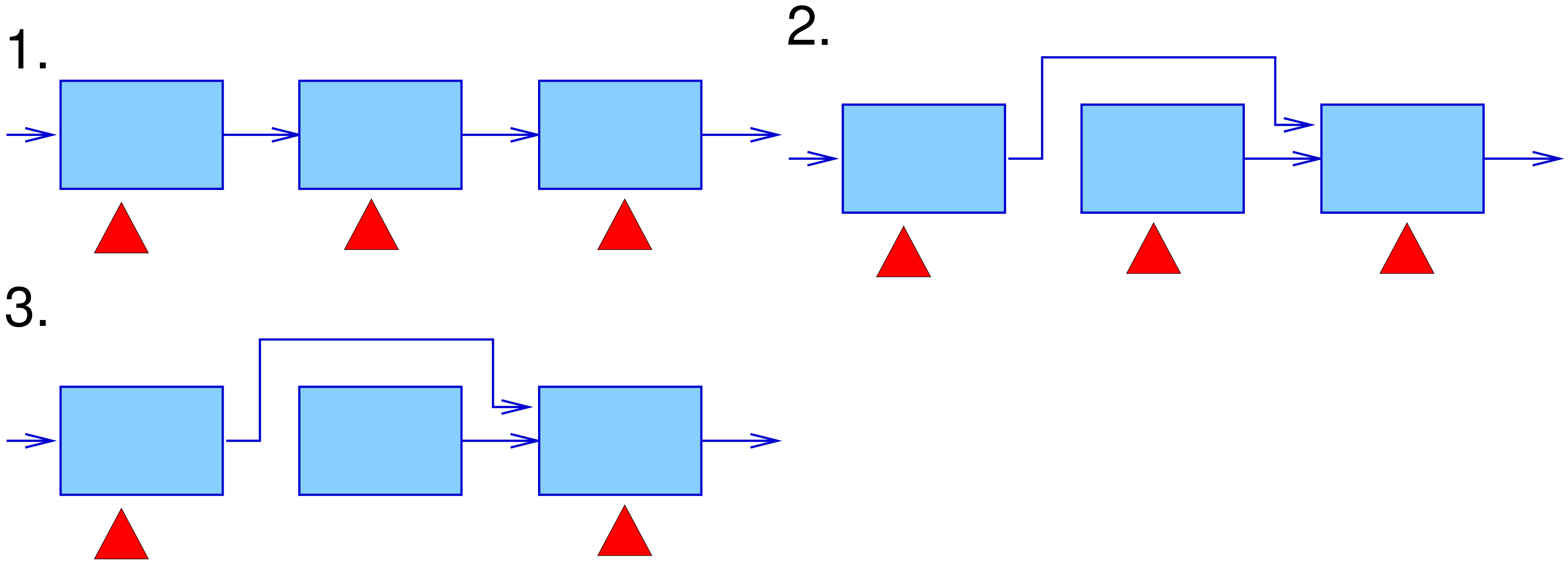

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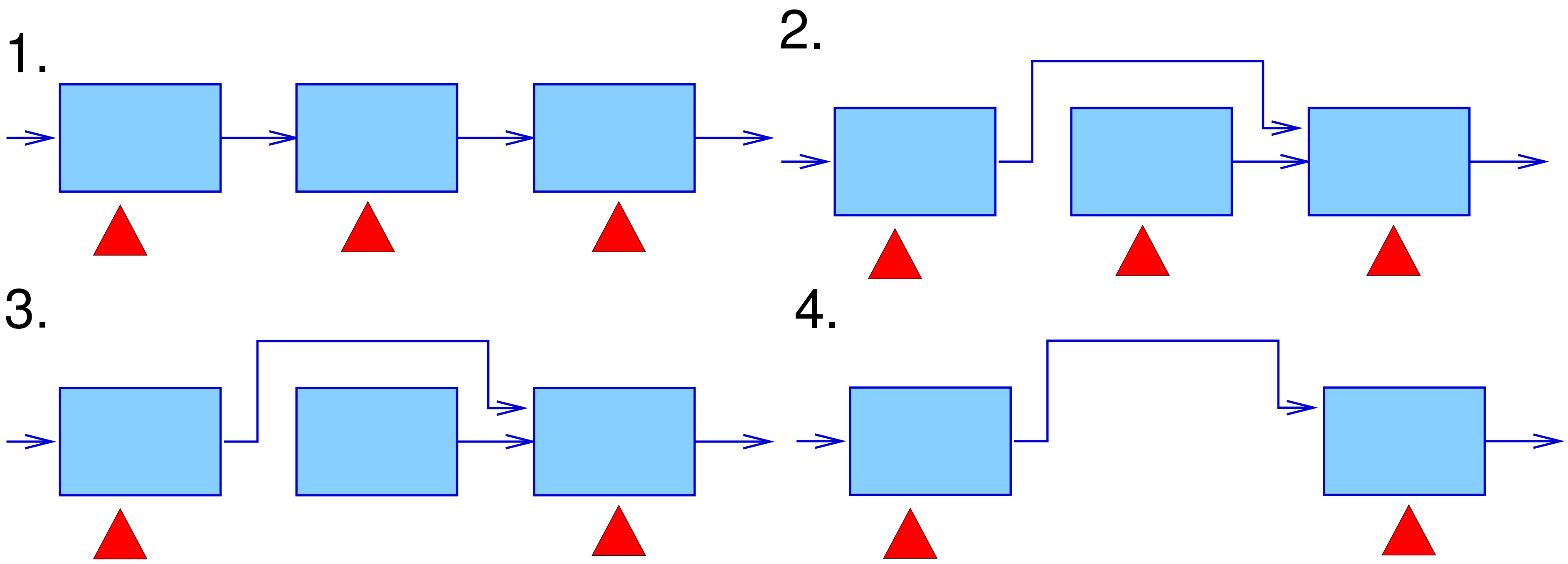

Doing without locks

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