Linux, Locking and Lots of Processors

Peter Chubb

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A LITTLE BIT OF HISTORY

NICTA

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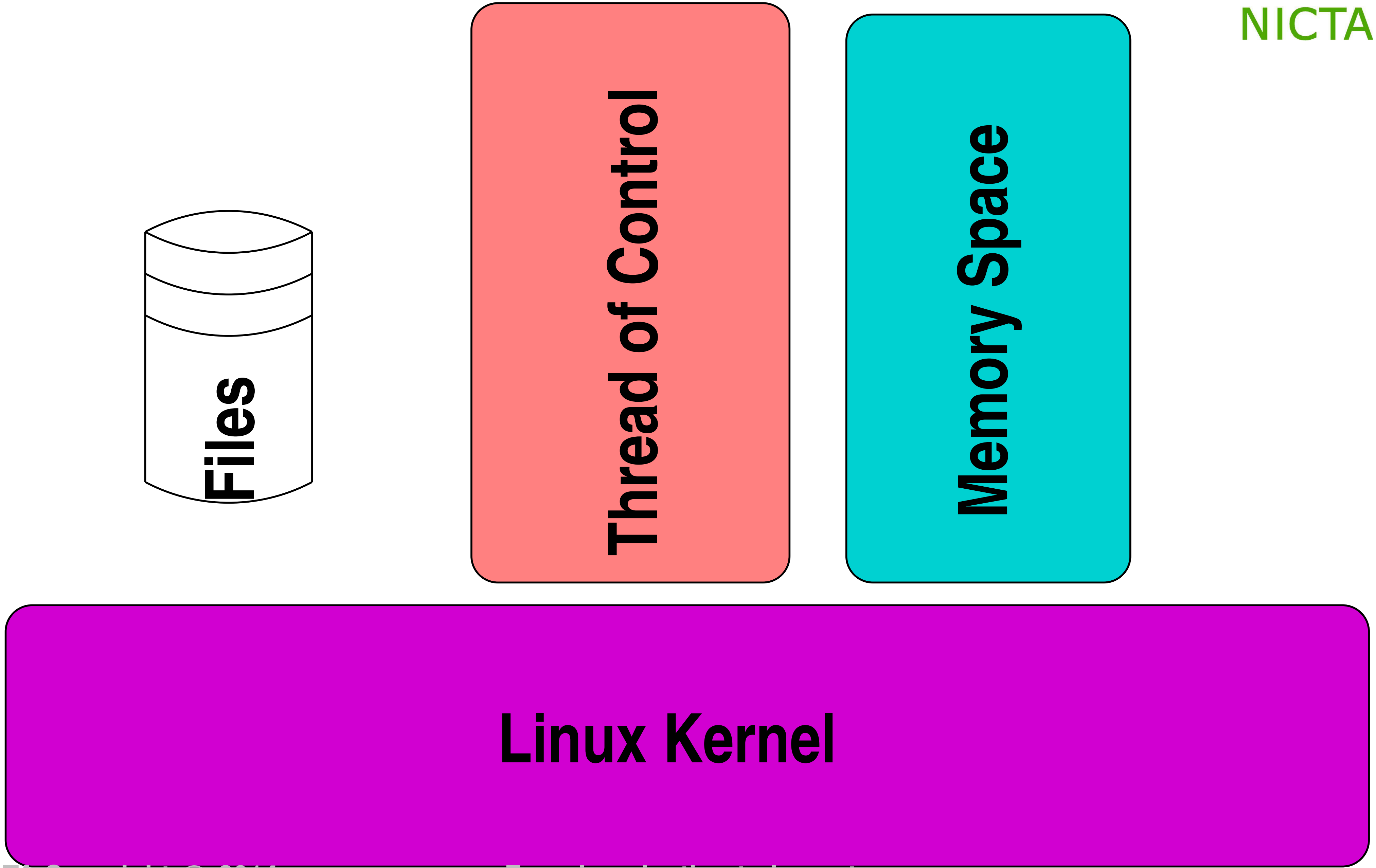
  - Paged virtual memory (3BSD, 1979)
  - TCP/IP Networking (BSD 4.1, 1983)
  - Multiprocessing (Vendor Unices such as Sequent's 'Balance', 1984)

ABSTRACTIONS



PROCESS MODEL

- Root process (`init`)
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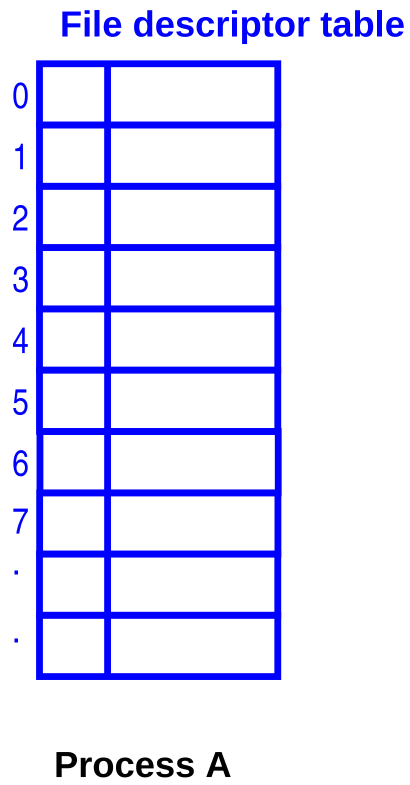
- `exec()` overwrites memory image from a file
- Allows a process to control what is shared

FORK() AND EXEC()

NICTA

- 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

Files and Processes:



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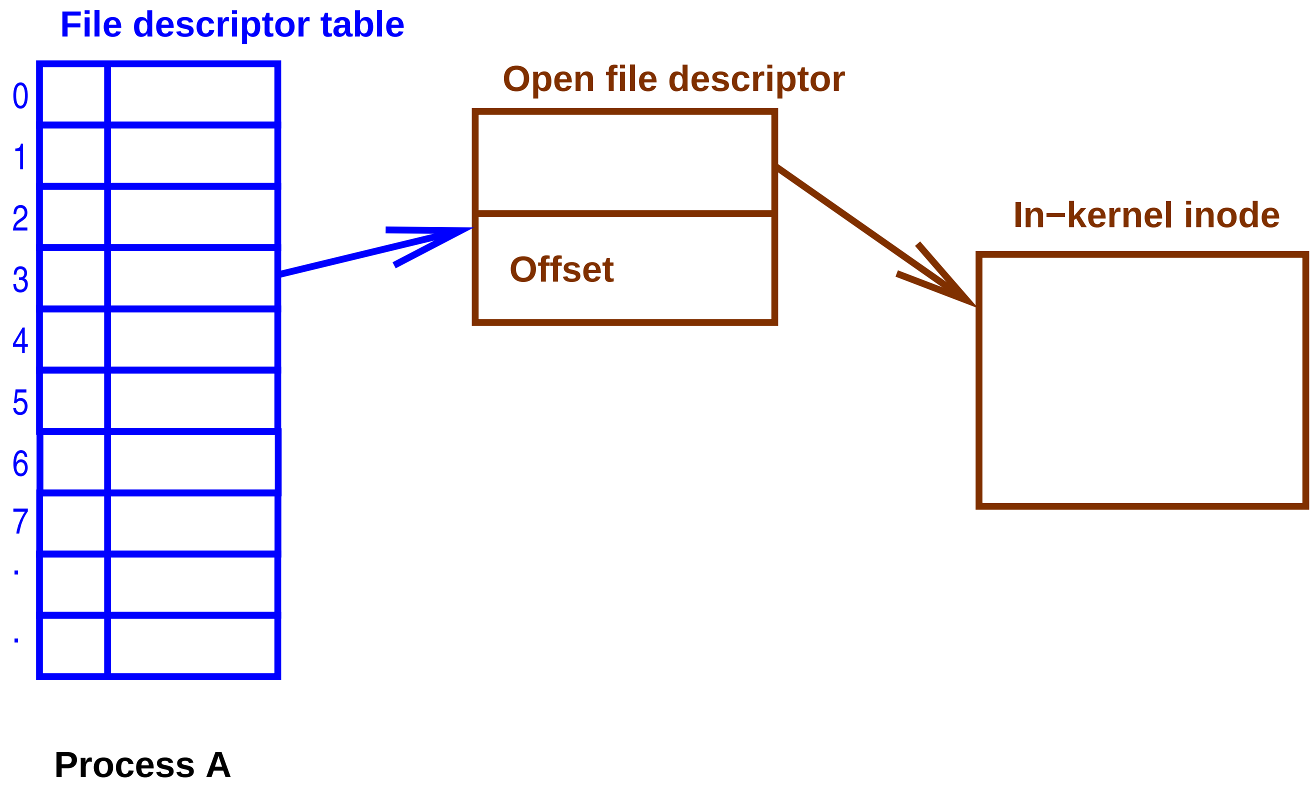

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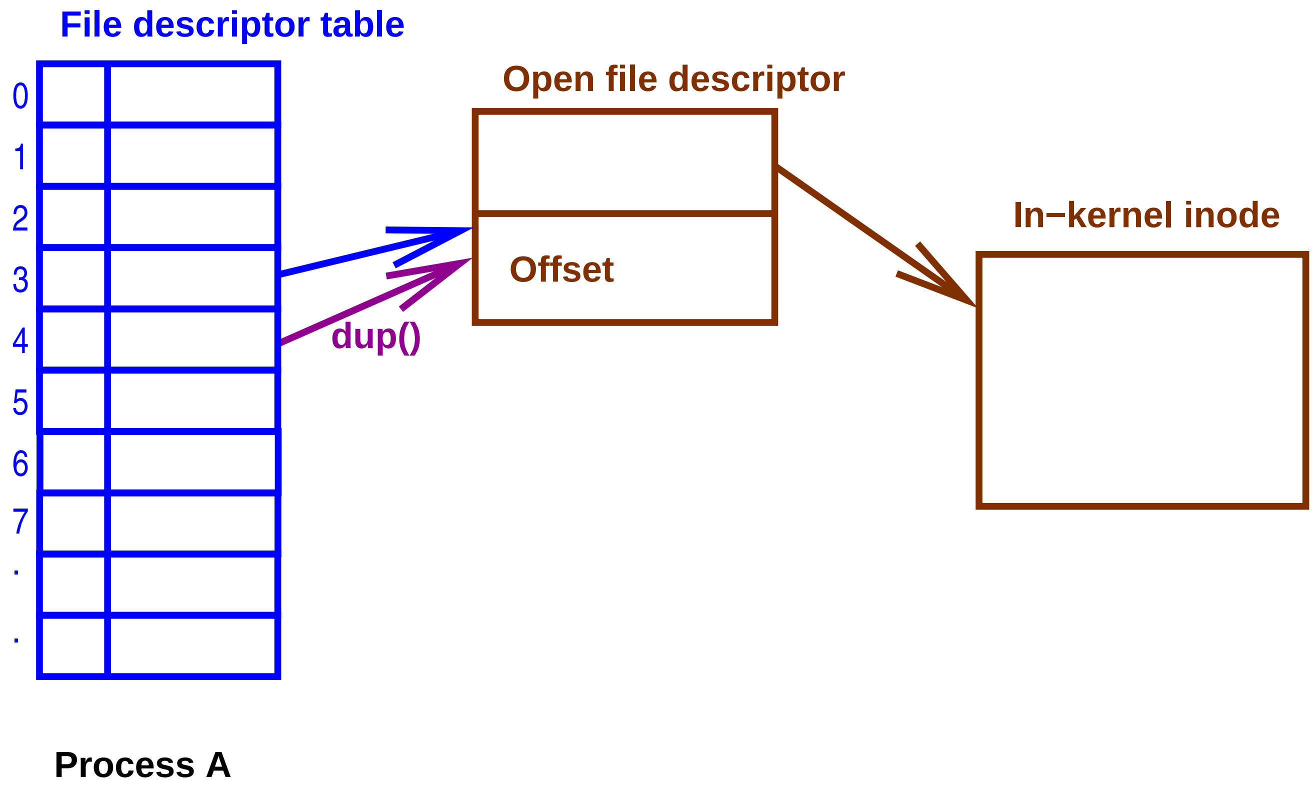

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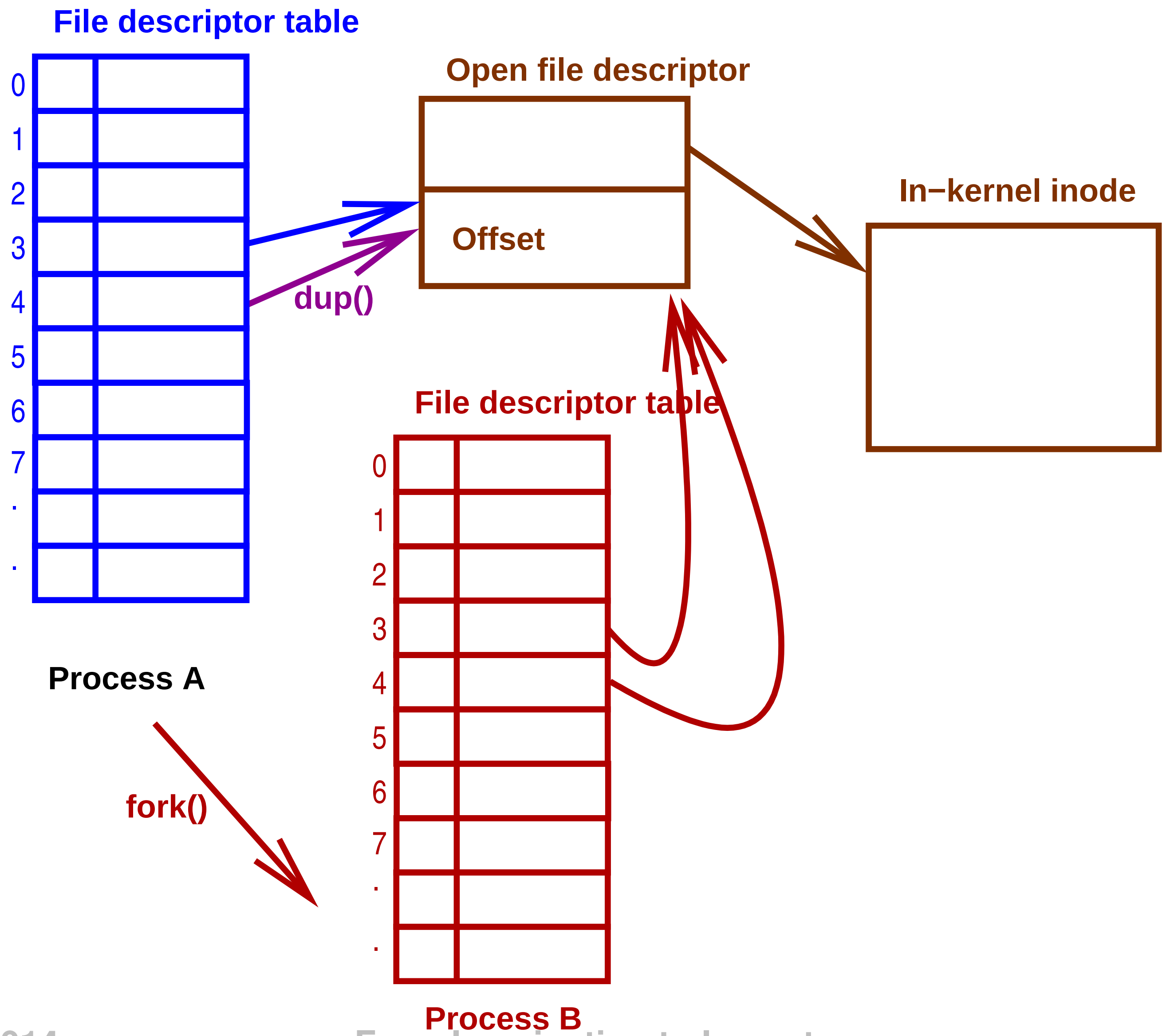


fork() and exec()

```
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

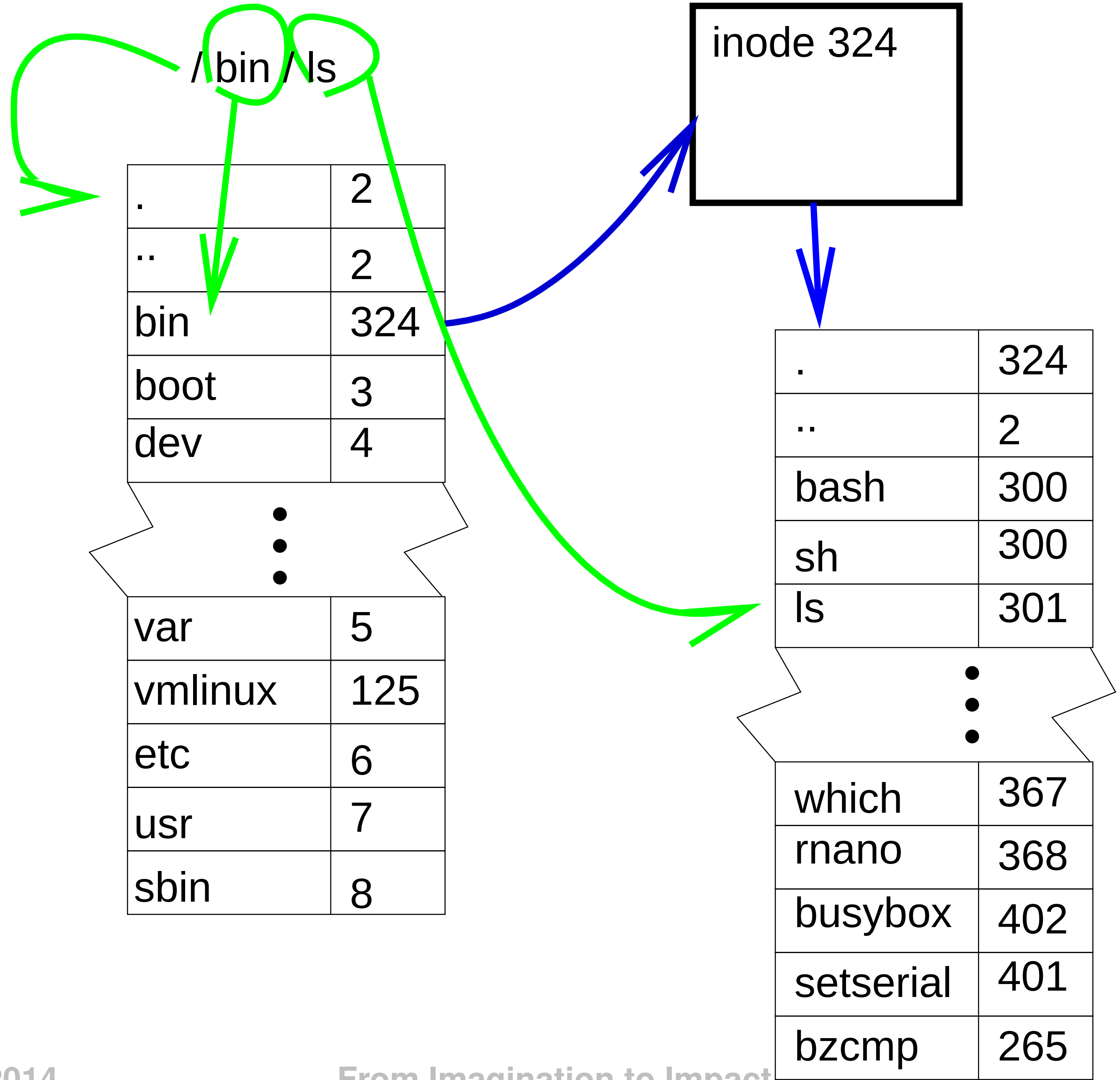
➜ Inherited from parent

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

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

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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EVOLUTION

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  - ➜ Easy to show correctness
  - ➜ Fast to implement
- ➜ As drawbacks and bottlenecks are found, replace with faster/more scalable alternatives

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`

C DIALECT

- Extra iterators
  - *type_name*`_foreach()`
- Extra accessors
  - `container_of()`

C Dialect

- Massive use of inline functions
- Some use of CPP macros
- Little `#ifdef` use in code: rely on optimizer to elide dead code.

SCHEDULING

Goals:

- O(1) in number of runnable processes, number of processors
  - good uniprocessor performance
- 'fair'
- Good interactive response
- topology-aware

SCHEDULING

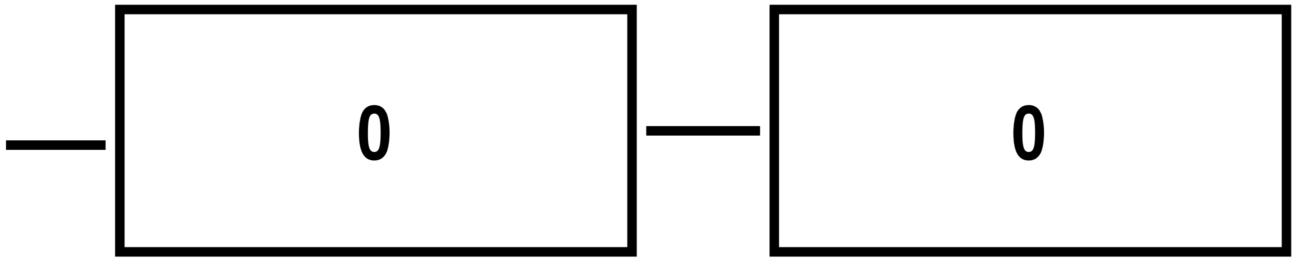
Implementation:

- Changes from time to time.
- Currently 'CFS' by Ingo Molnar.

Dual Entitlement Scheduler

Running

Expired



Scheduling

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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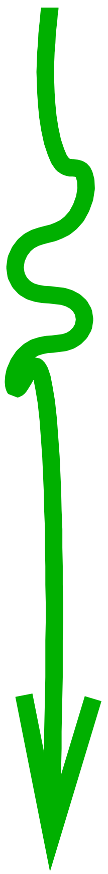
2. Always run left-most task.

Devil's in the details:

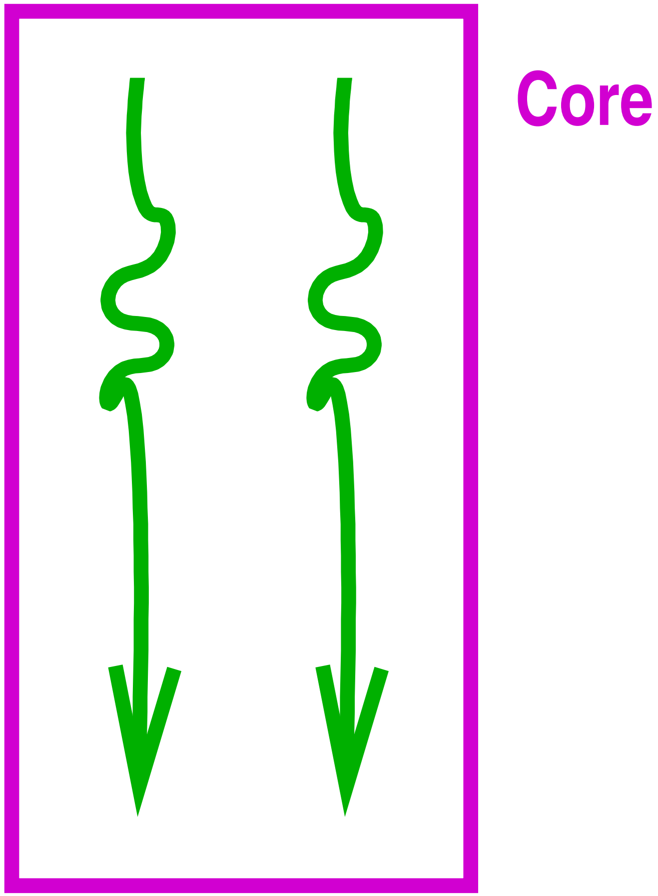
- Avoiding overflow
- Keeping recent history
- multiprocessor locality
- handling too-many threads
- Sleeping tasks
- Group hierarchy

SCHEDULING



(hyper)Thread

SCHEDULING



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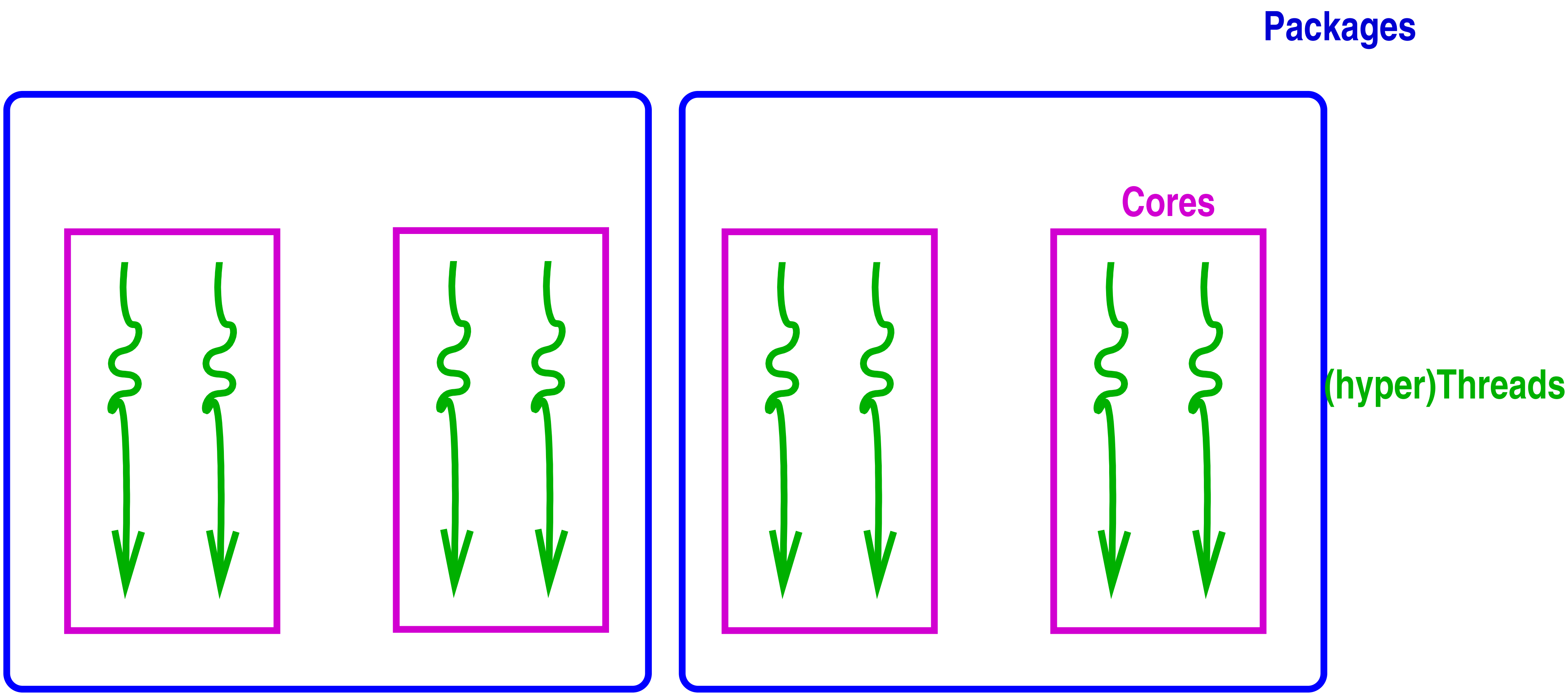

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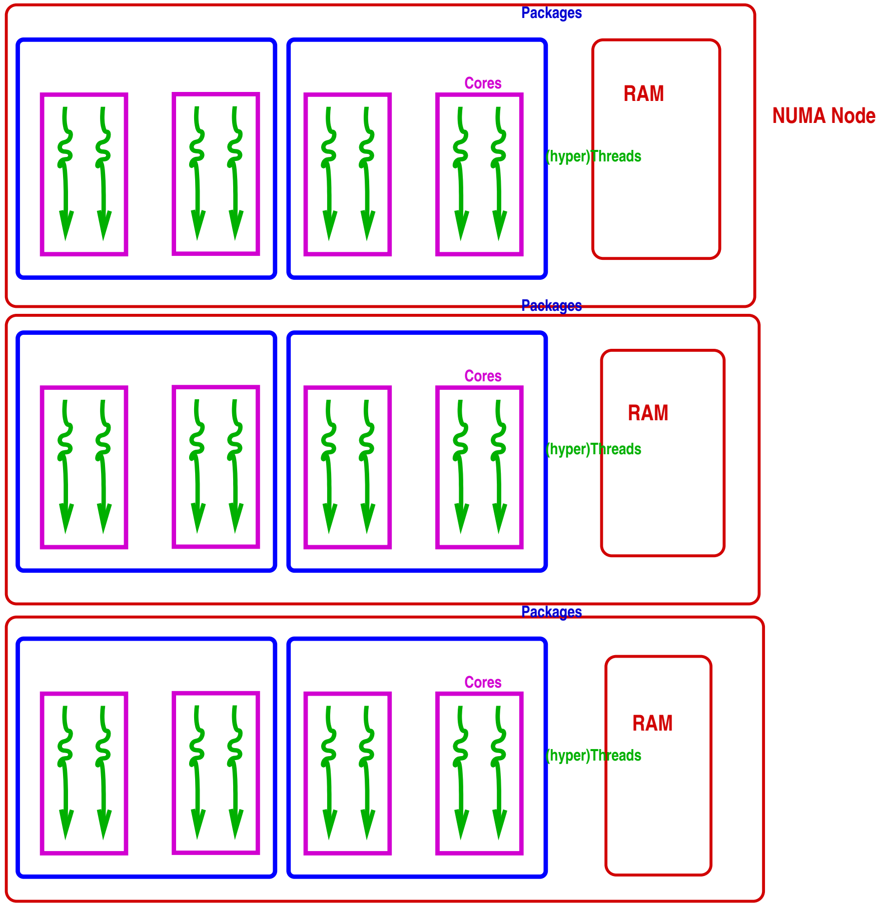
NICTA



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Locality Issues:

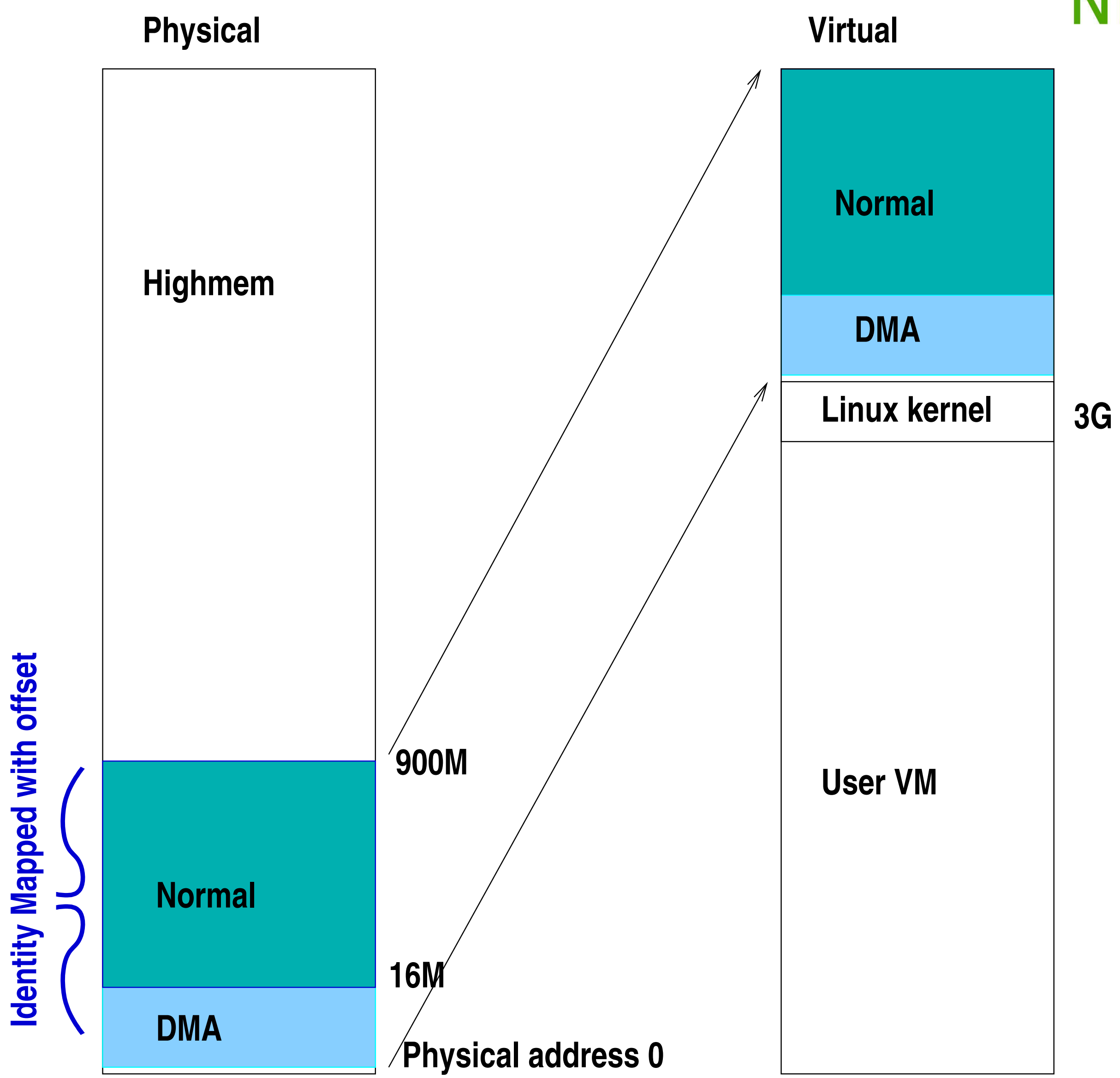
- Best to reschedule on same processor (don’t move cache footprint, keep memory close)
  - Otherwise schedule on a ‘nearby’ processor
- Try to keep whole sockets idle
- Somehow identify cooperating threads, co-schedule on same package?

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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- small memory systems have all memory as logical
- More memory $\rightarrow \Delta$ kernel refer to memory by `struct page`

MEMORY MANAGEMENT

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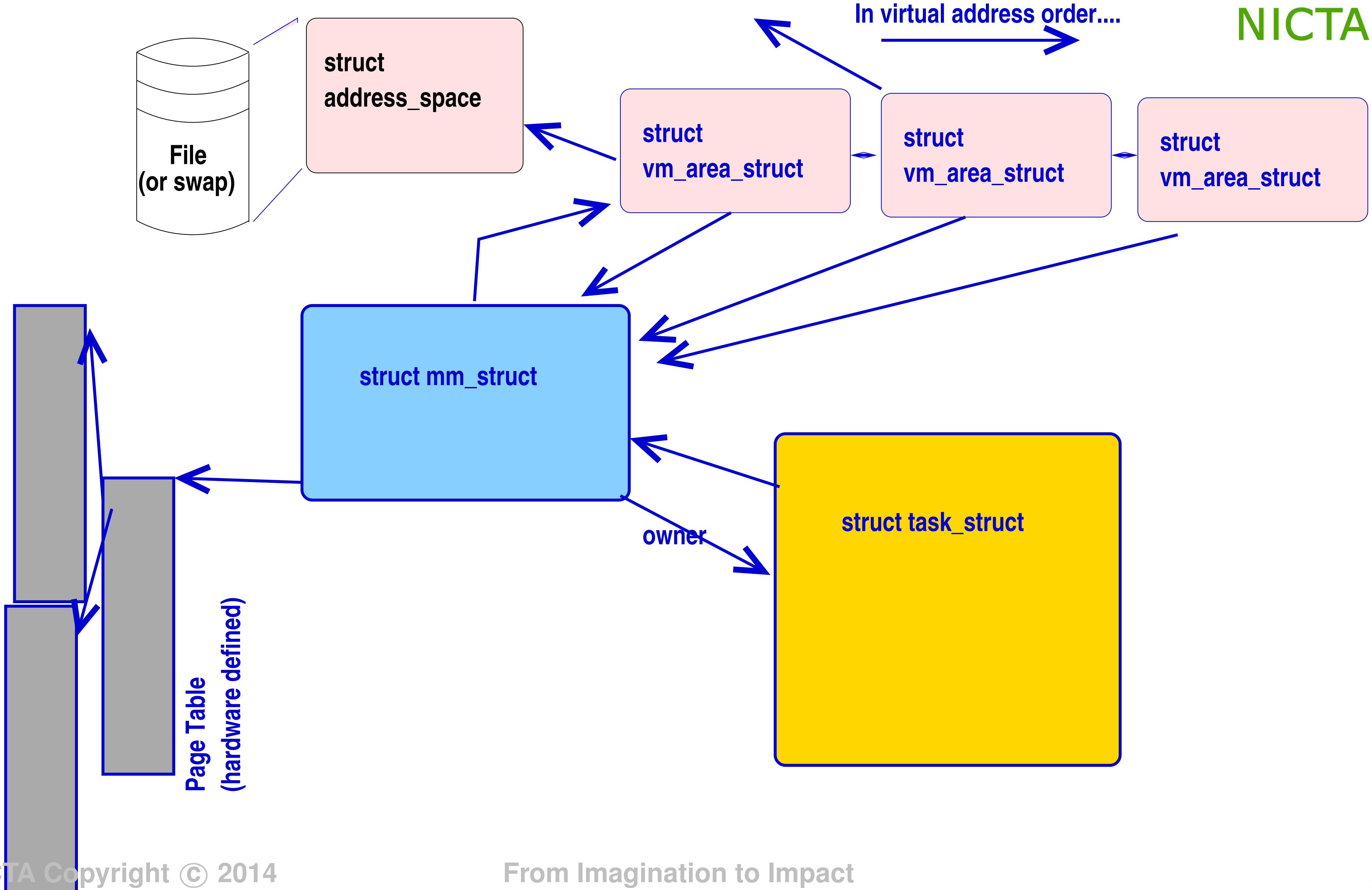
`struct page`:

- 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



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

MEMORY MANAGEMENT

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_
{ PCI_DEVICE(PCI_VENDOR_ID_TTTECH,PCI_DEVICE_ID_T
{ },
};
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:

```
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

SUMMARY

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- I've told you status today

SUMMARY

- I’ve told you status today
  - 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

FILE SYSTEMS

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I'm assuming:

- You've already looked at ext[234]-like filesystems
- You've some awareness of issues around on-disk locality and I/O performance
- You understand issues around avoiding on-disk corruption by carefully ordering events, and/or by the use of a Journal.

NORMAL FILE SYSTEMS

- Optimised for use on spinning disk
- RAID optimised (especially XFS)
- Journals, snapshots, transactions...

Flash Memory

- NOR Flash
- NAND Flash

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FLASH MEMORY

NICTA

- NOR Flash
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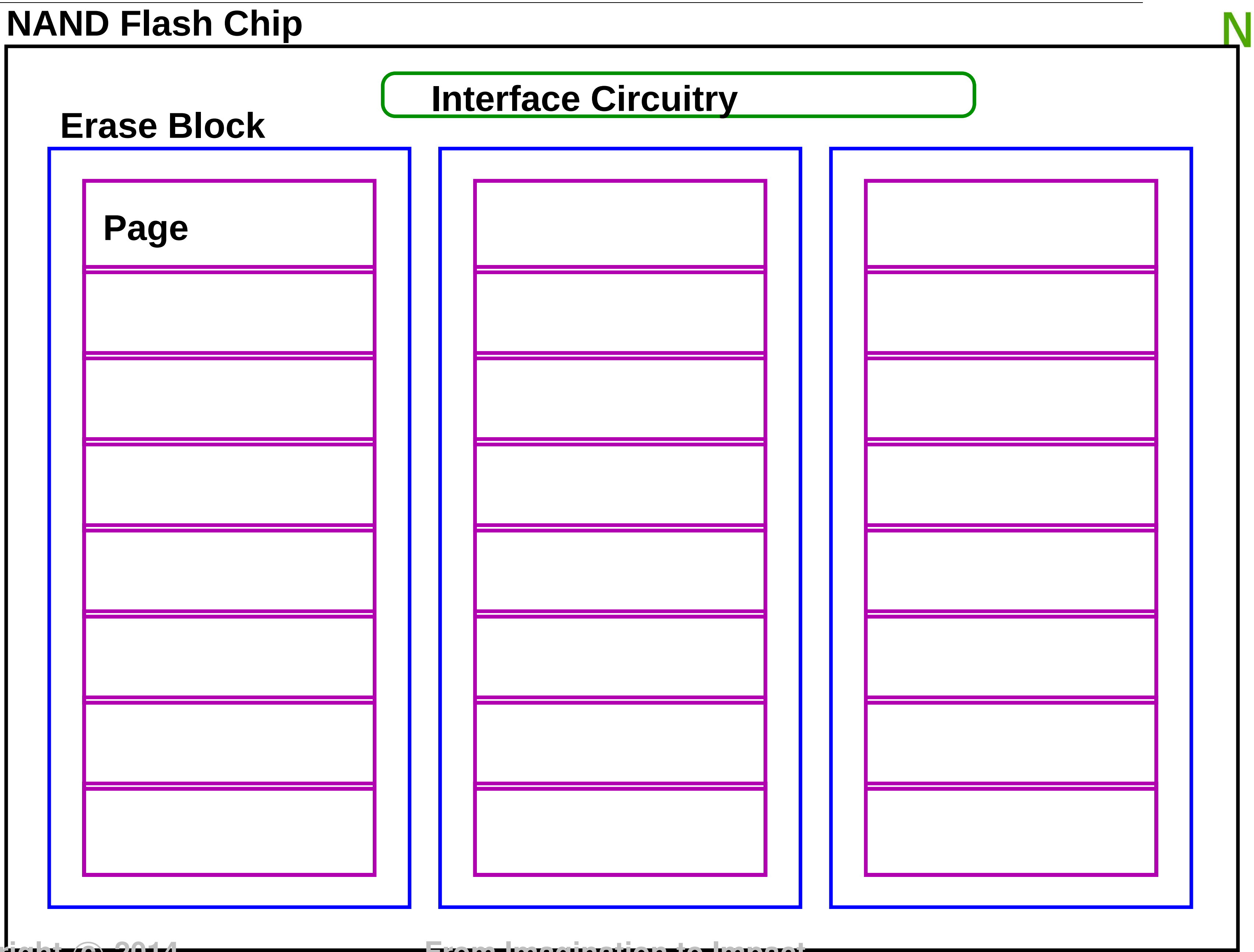
  - MTD — Memory Technology Device
  - eMMC, SDHC etc — A JEDEC standard
  - SSD, USB — and other disk-like interfaces

NAND CHARACTERISTICS



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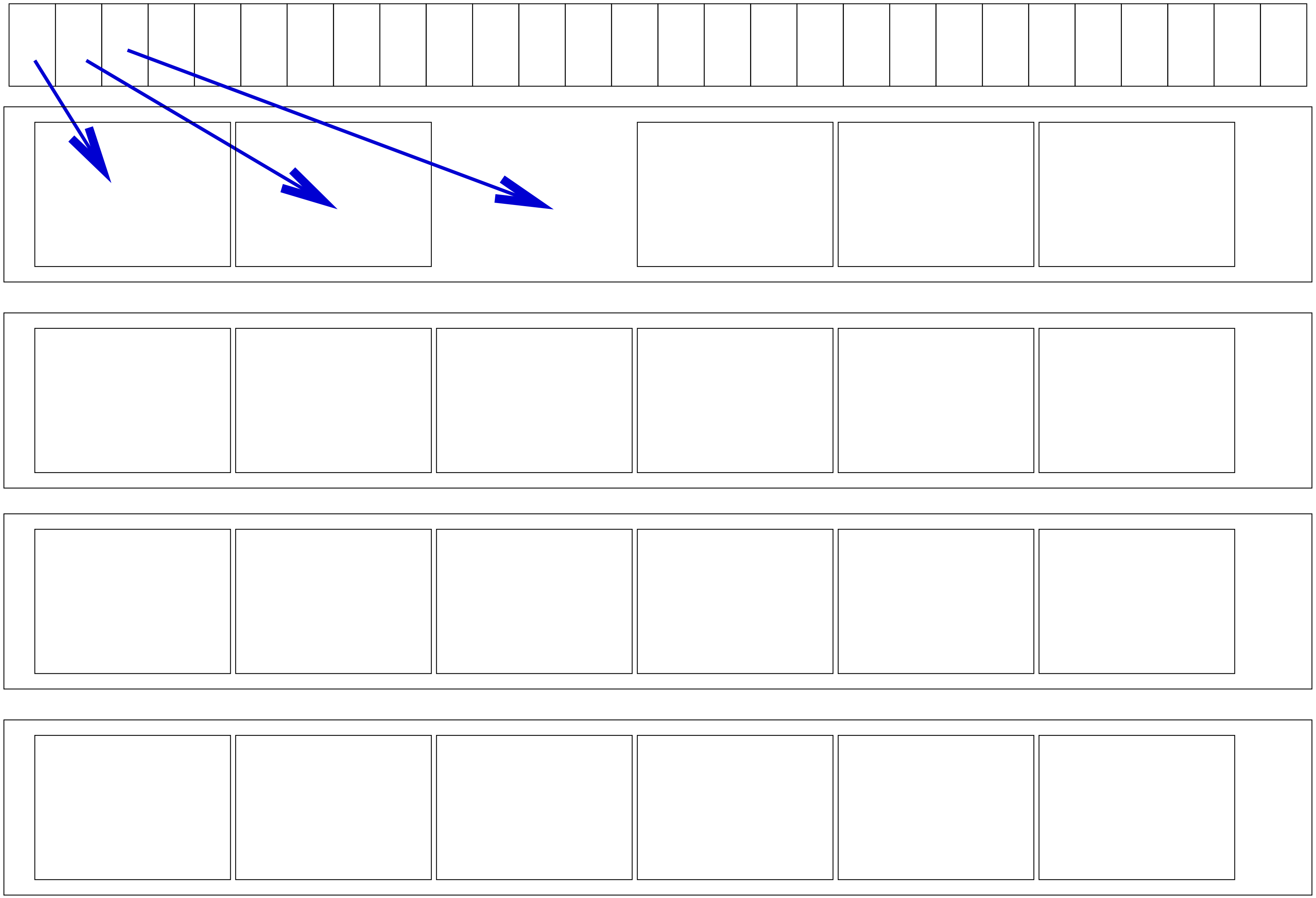

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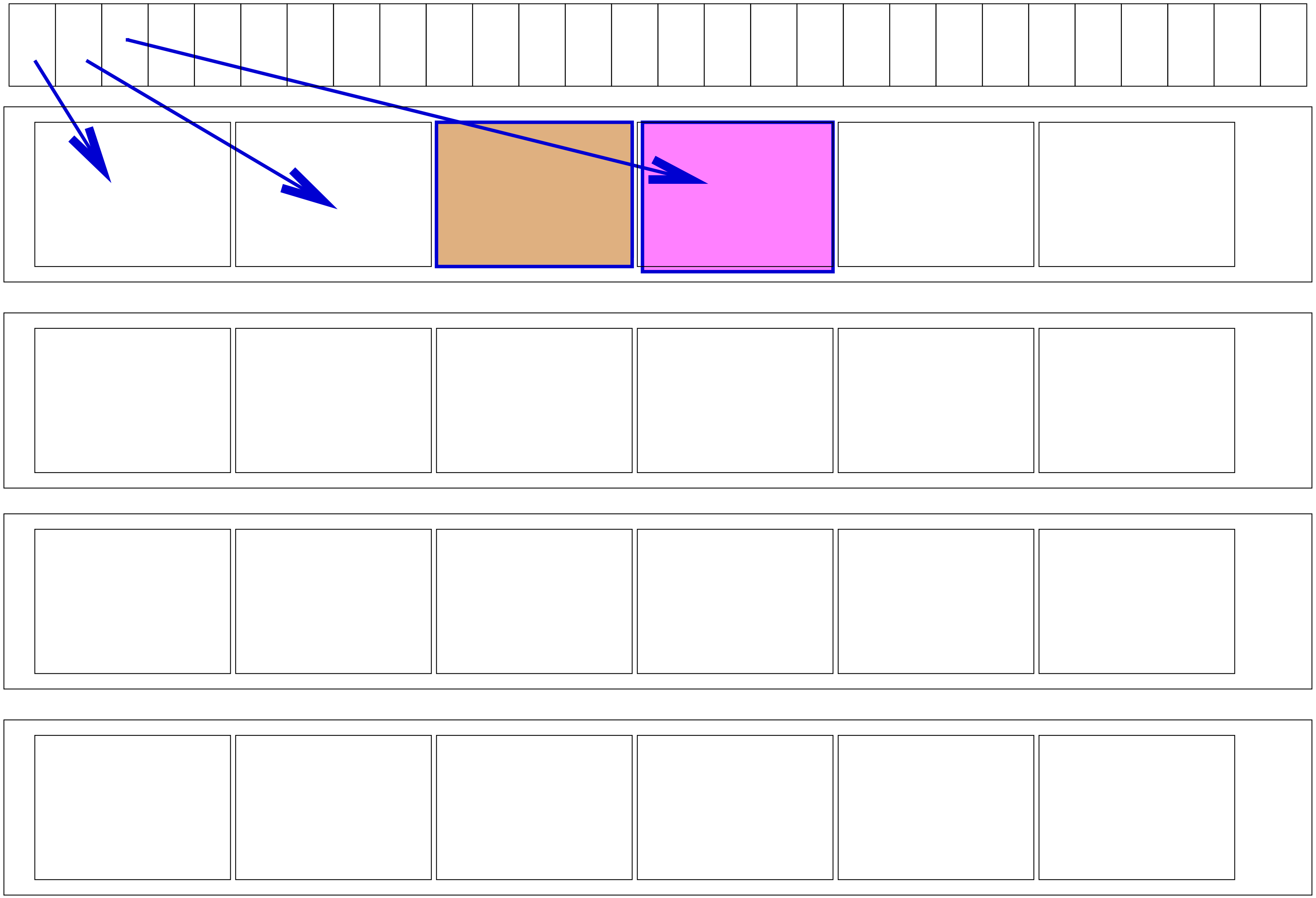

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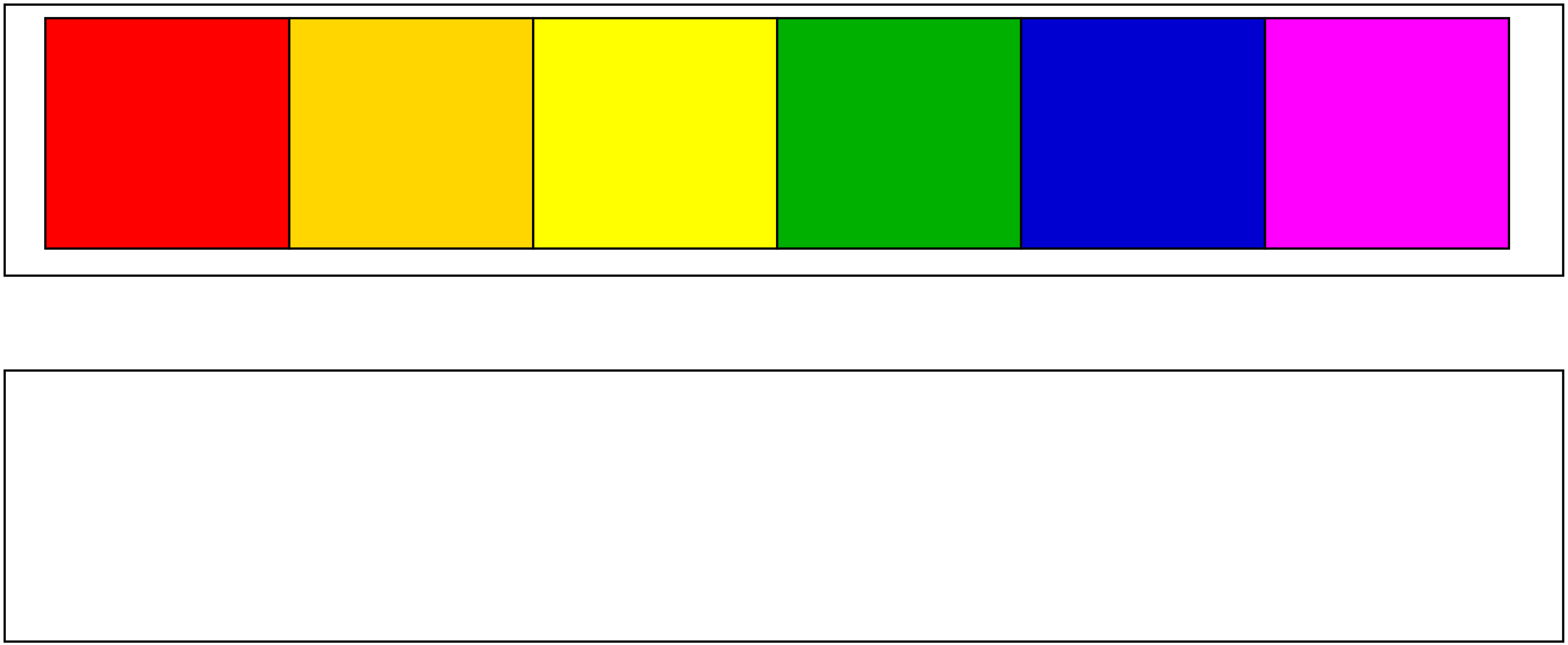

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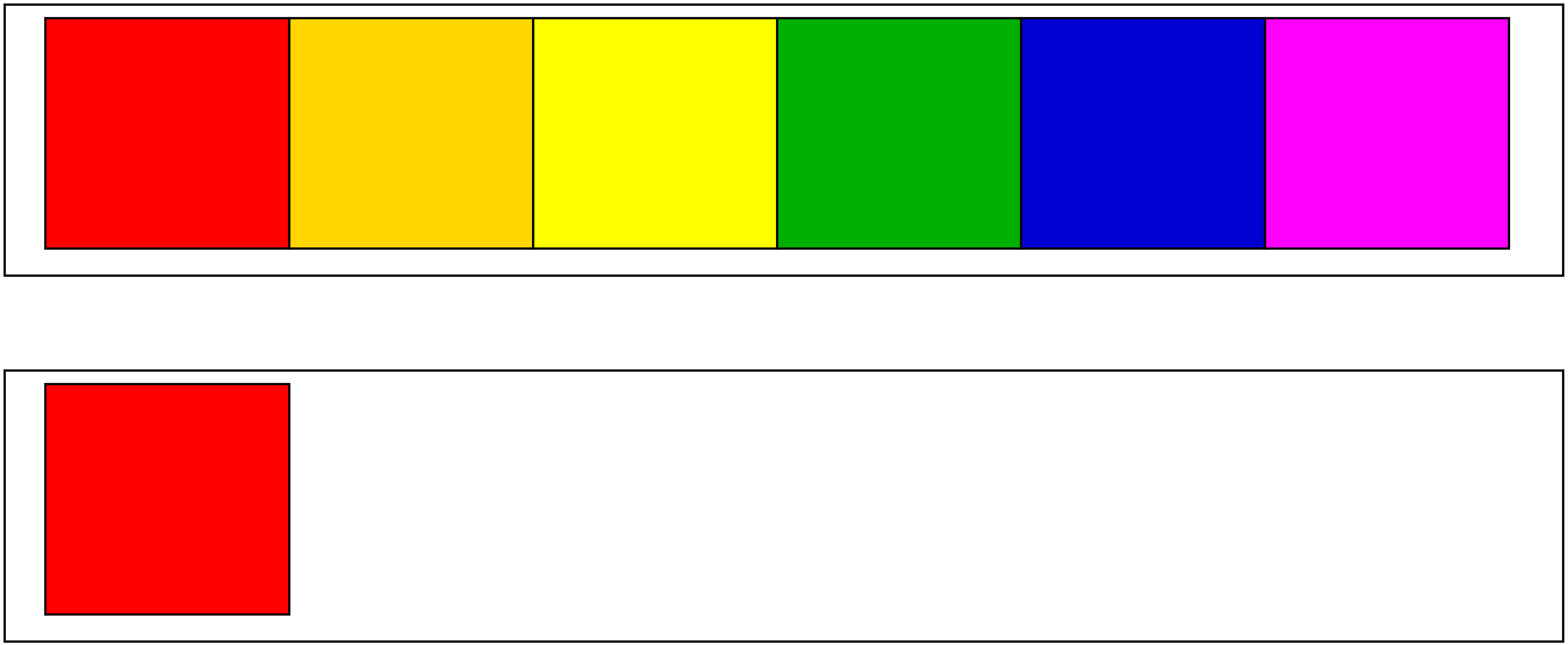

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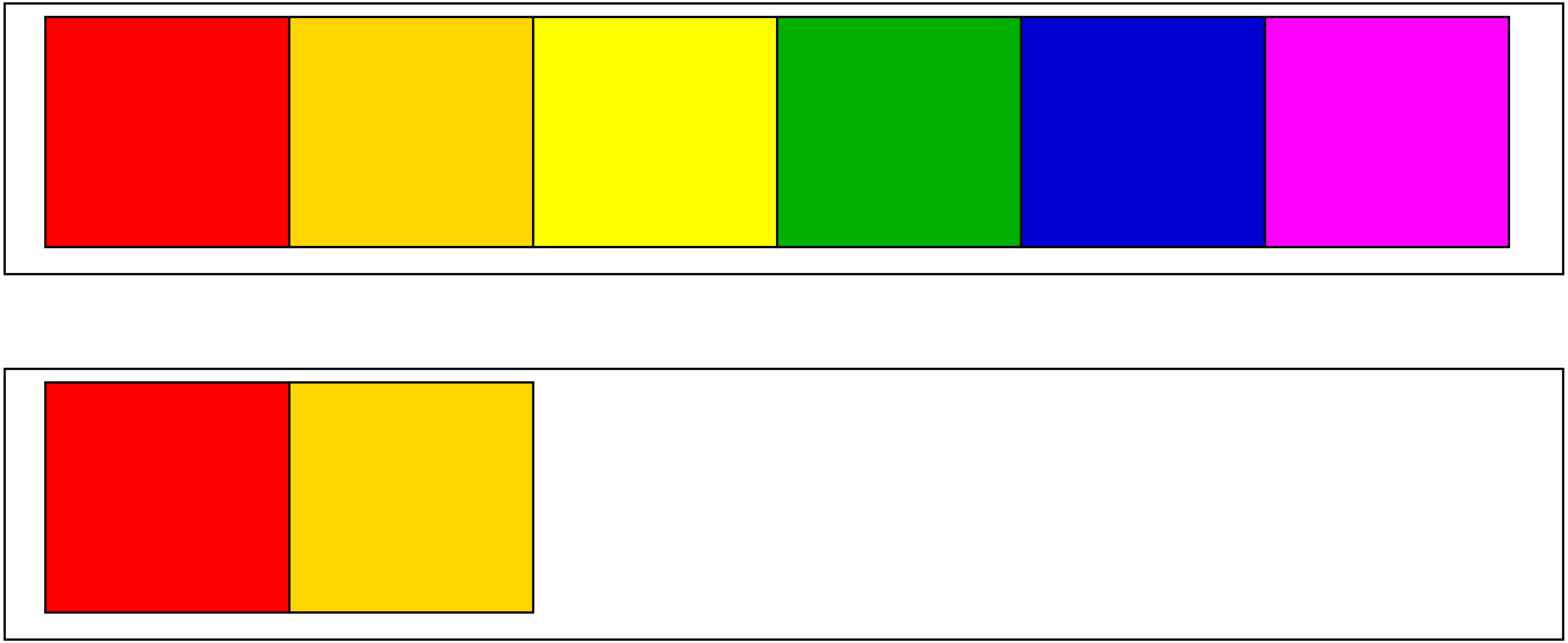

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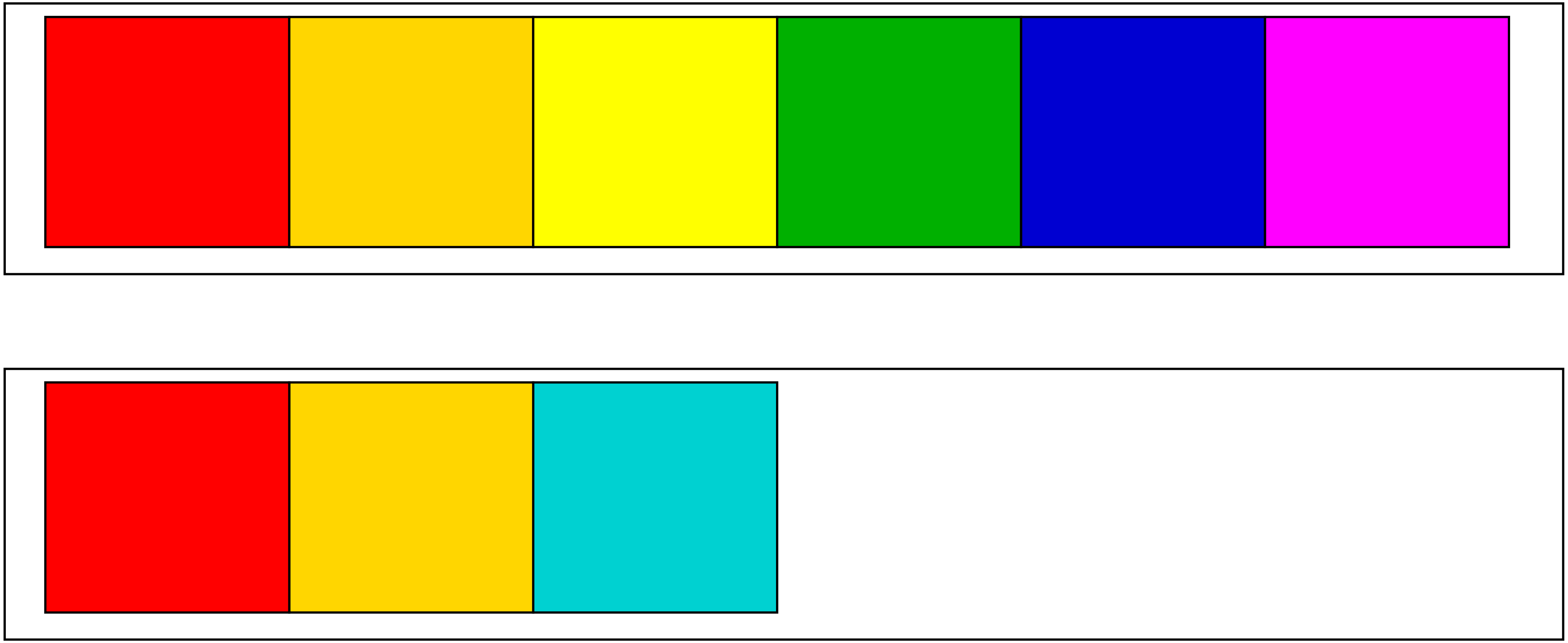

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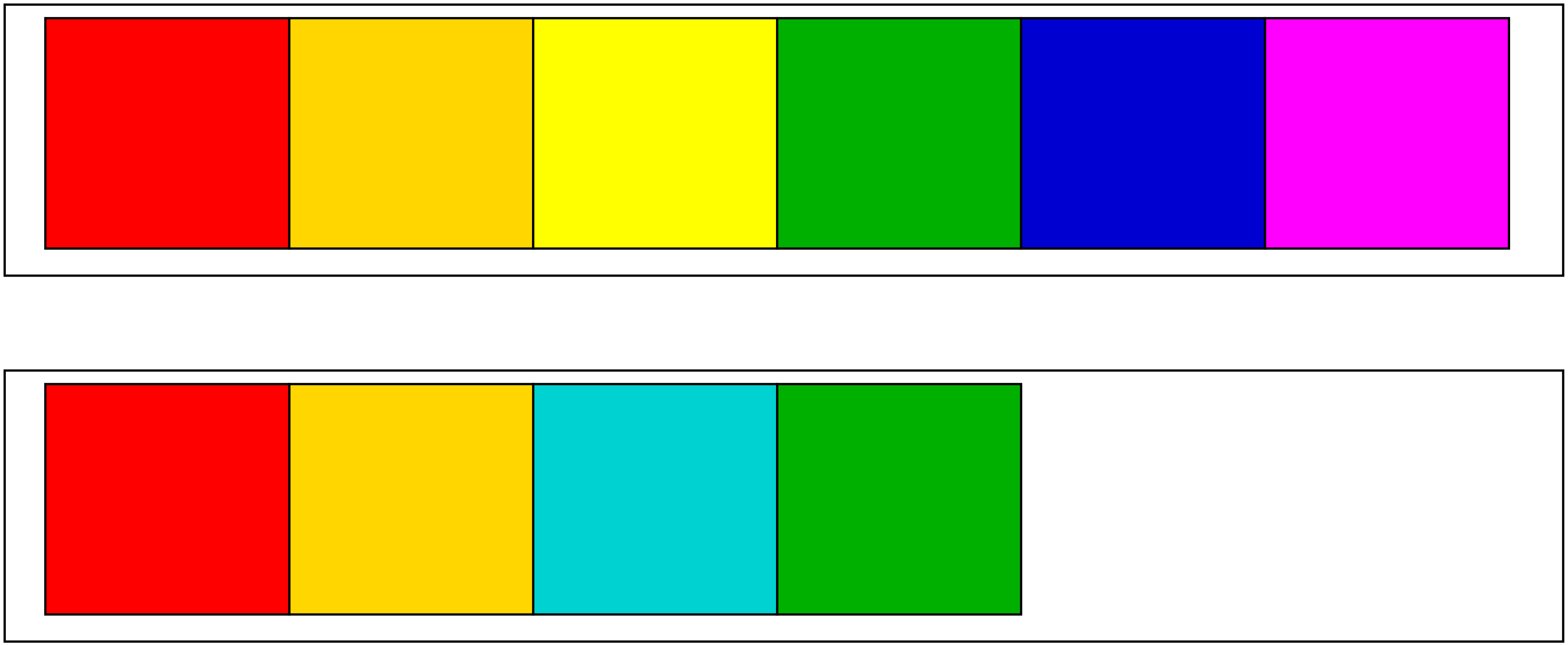

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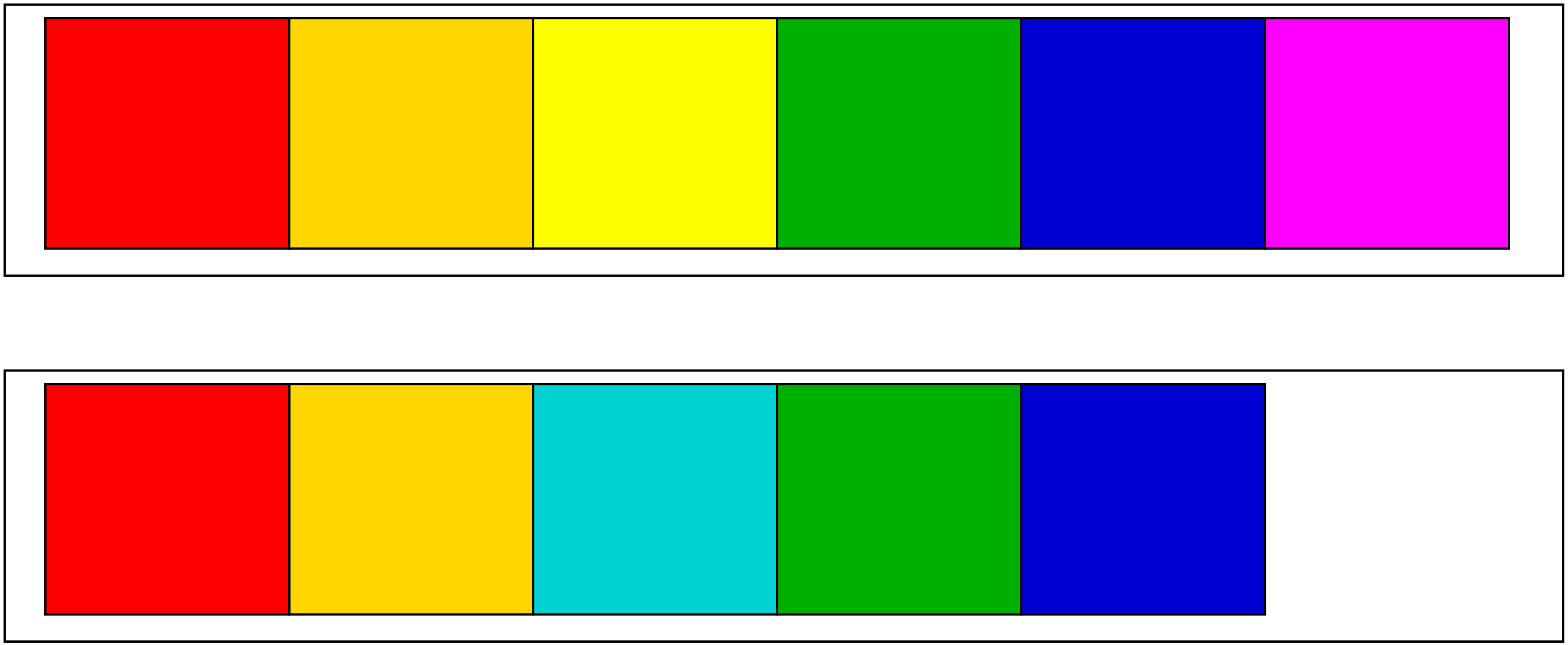

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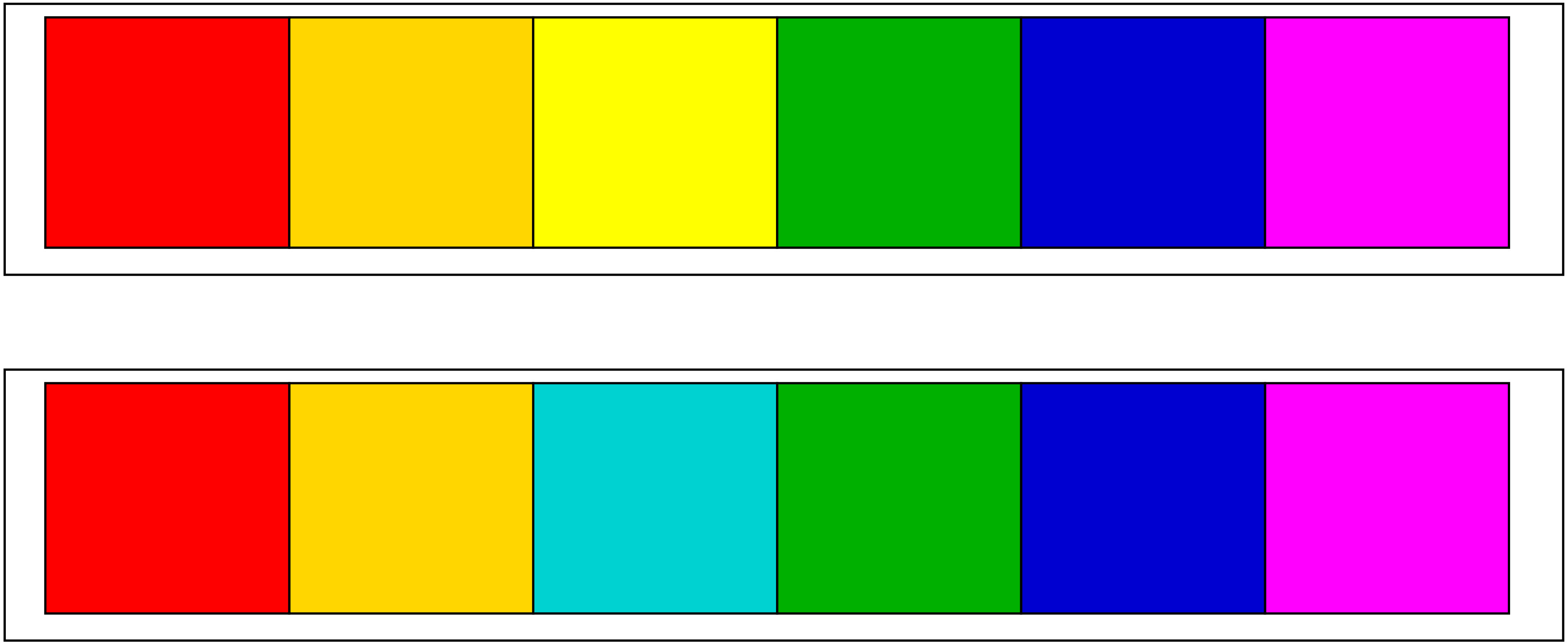

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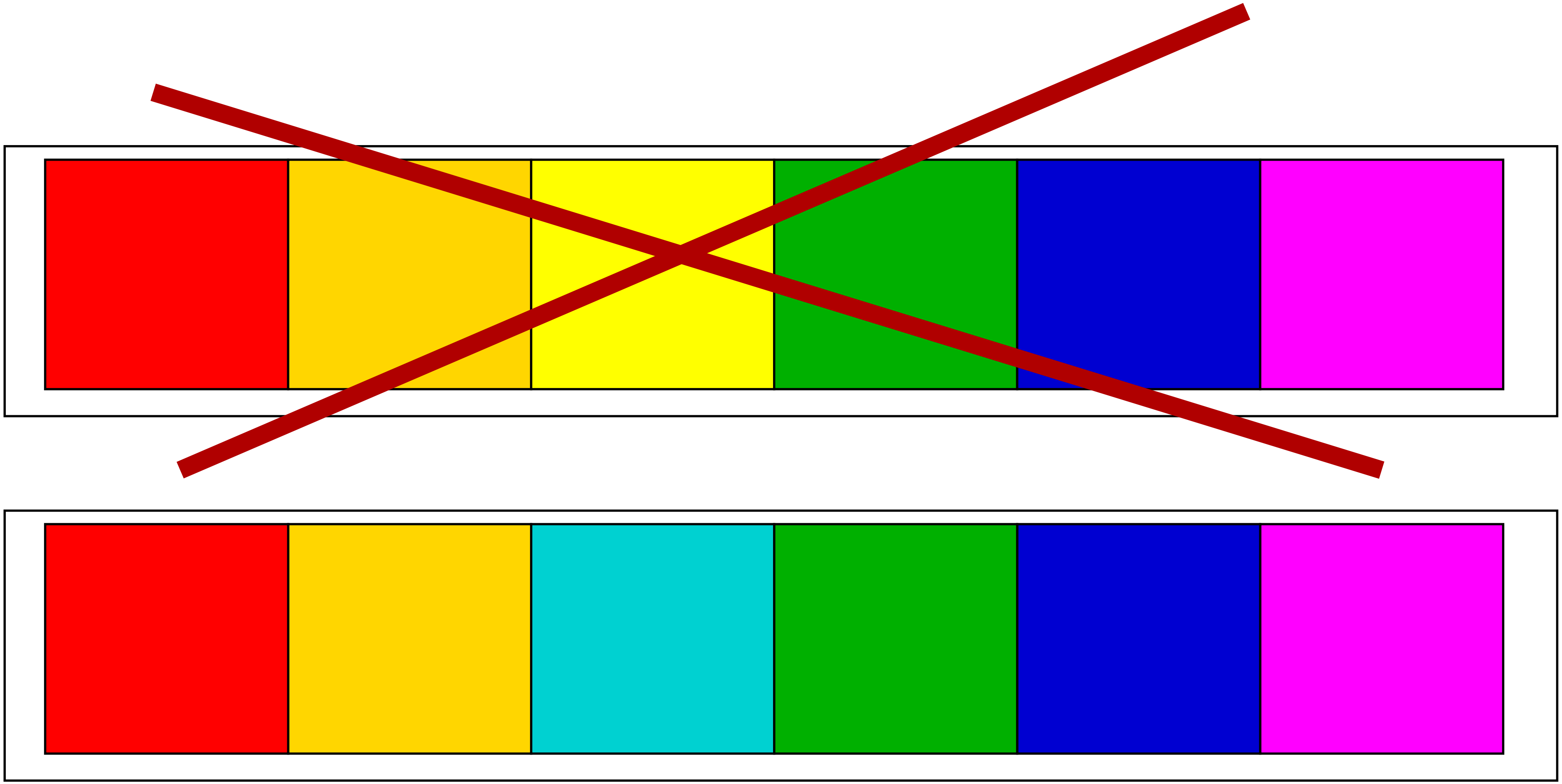

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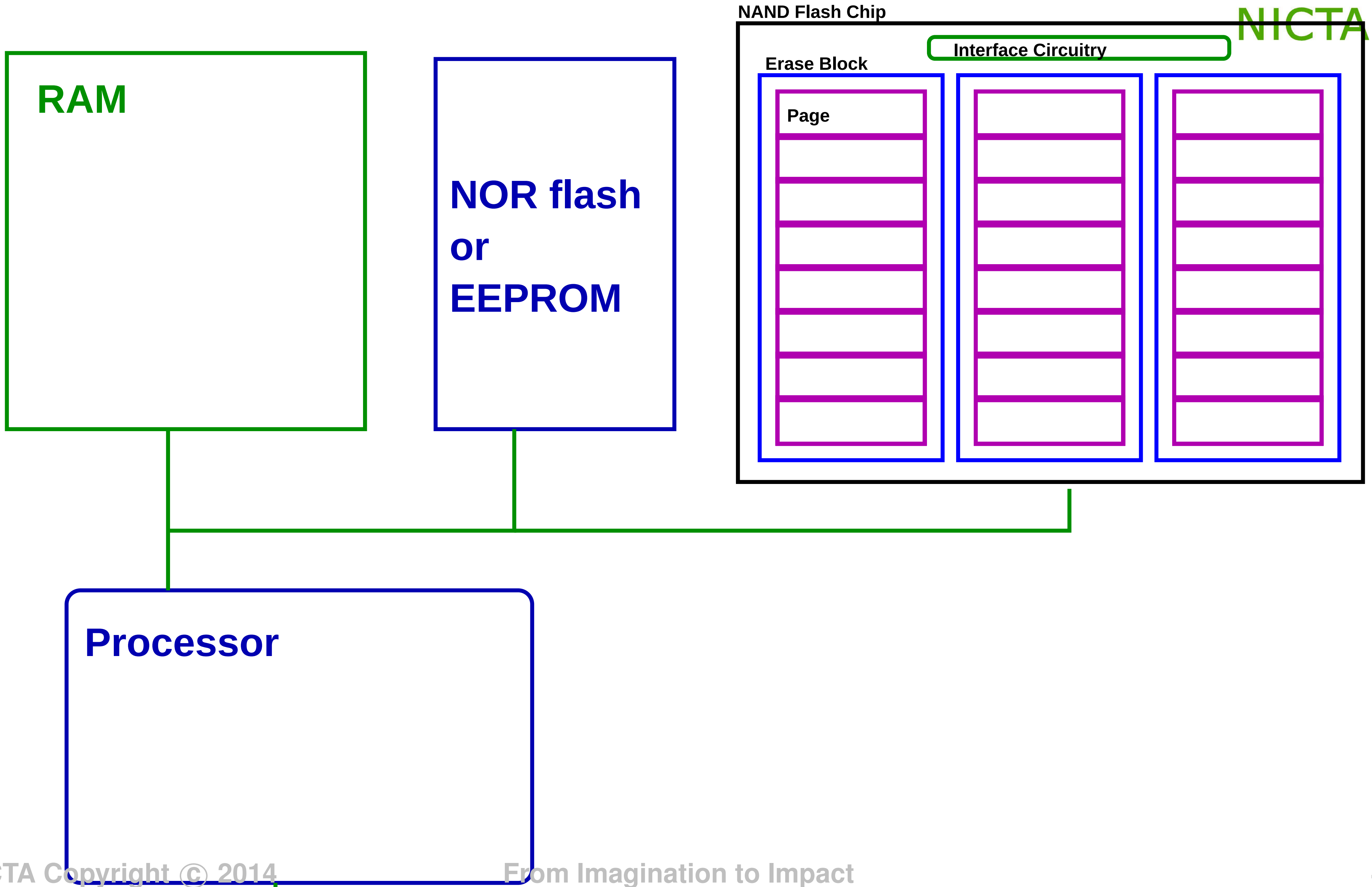

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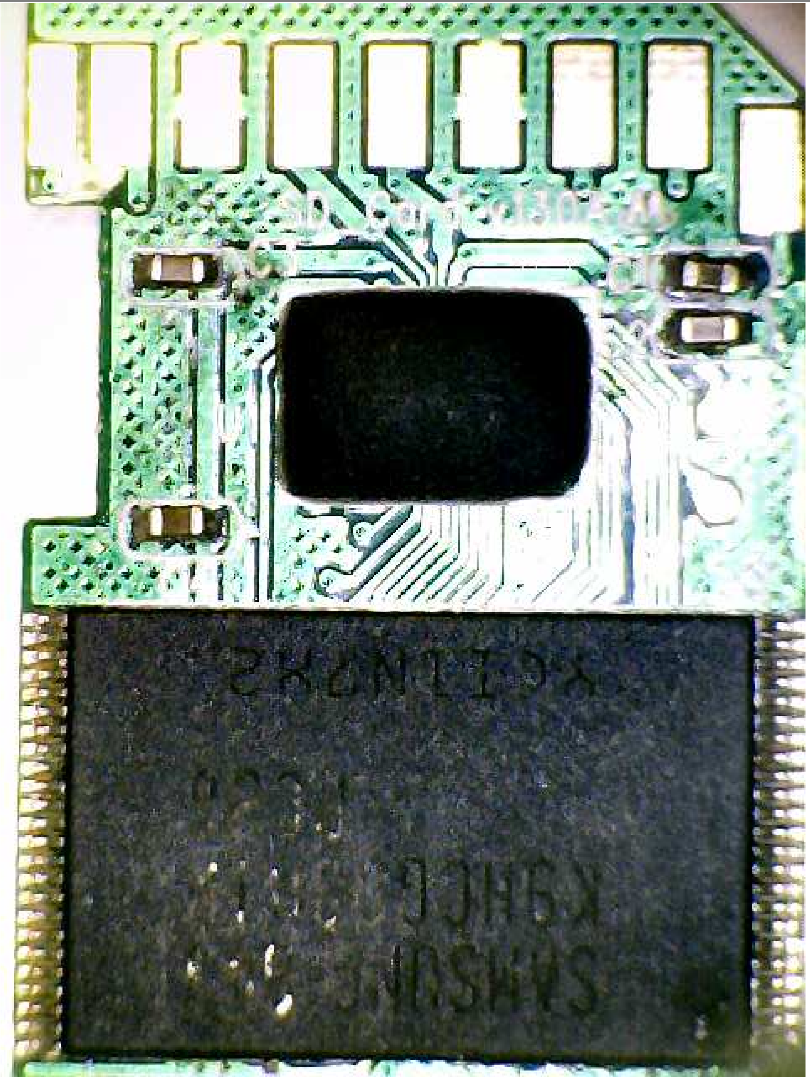

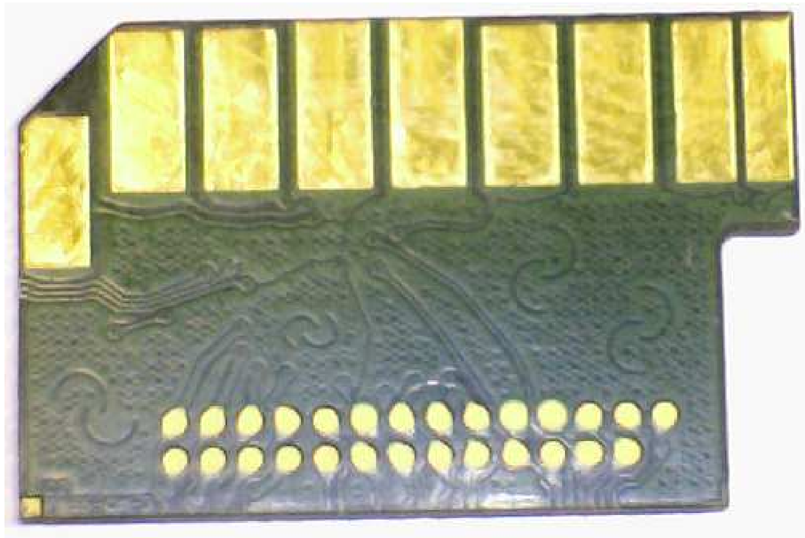

THE CONTROLLER:

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- Manages writes to prevent wearing out
- Manages reads to prevent read-disturb
- Performs garbage collection
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Mostly documented in Korean patents referred to by US patents!

WEAR MANAGEMENT

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Wear Management

Two ways:

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- Spread writes over all erase blocks (wear levelling)

In practice both are used.
Also:

- Count reads and schedule garbage collection after some threshhold

PREFORMAT

- Typically use FAT32 (or exFAT for sdxc cards)
- Always do cluster-size I/O (64k)
- First partition segment-aligned

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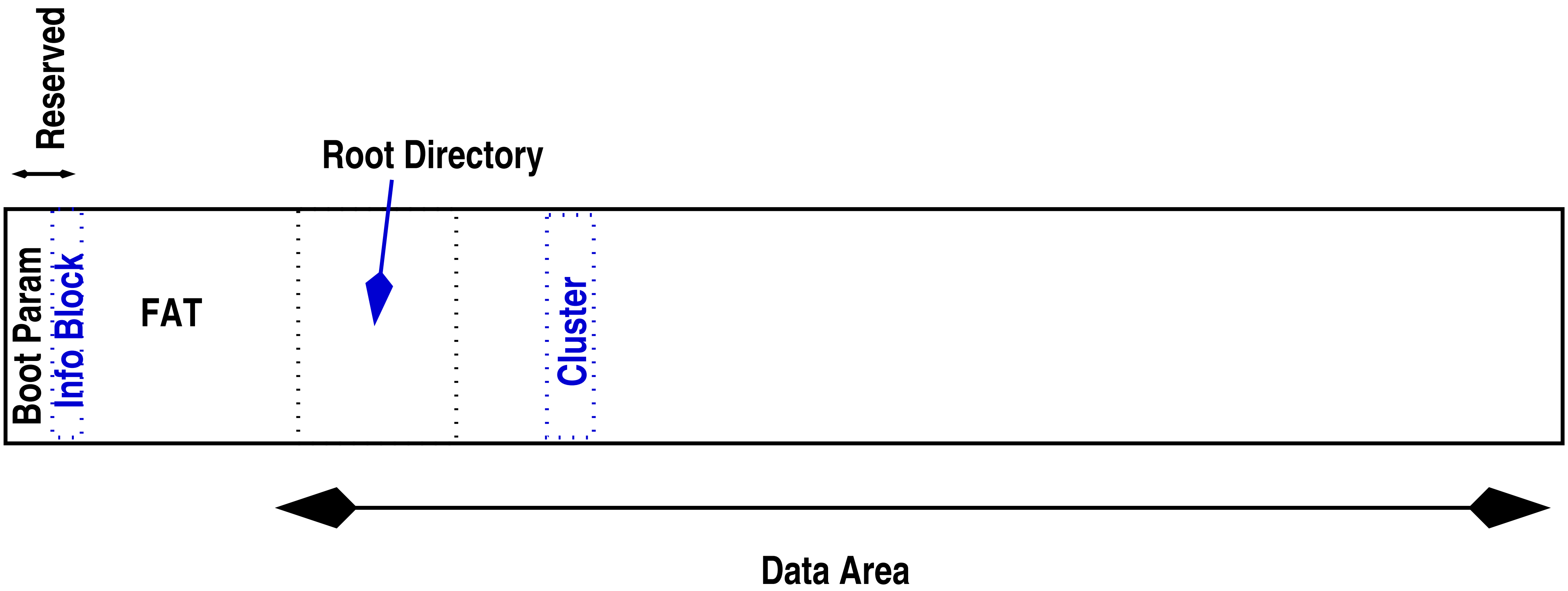
  Conjecture Flash controller optimises for the preformatted FAT fs

FAT FILE SYSTEMS



FAT FILE SYSTEMS

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Conjecture The controller has some number of buffers it treats specially, to allow more than one write locus.

TESTING SDHC CARDS

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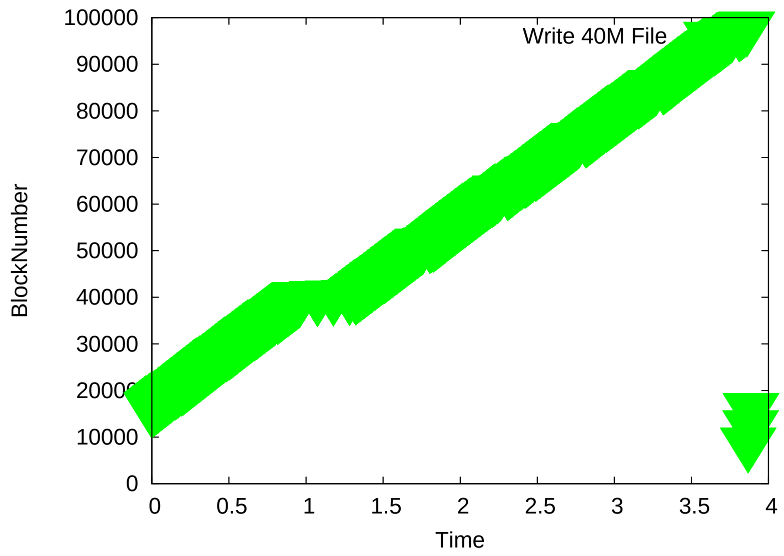
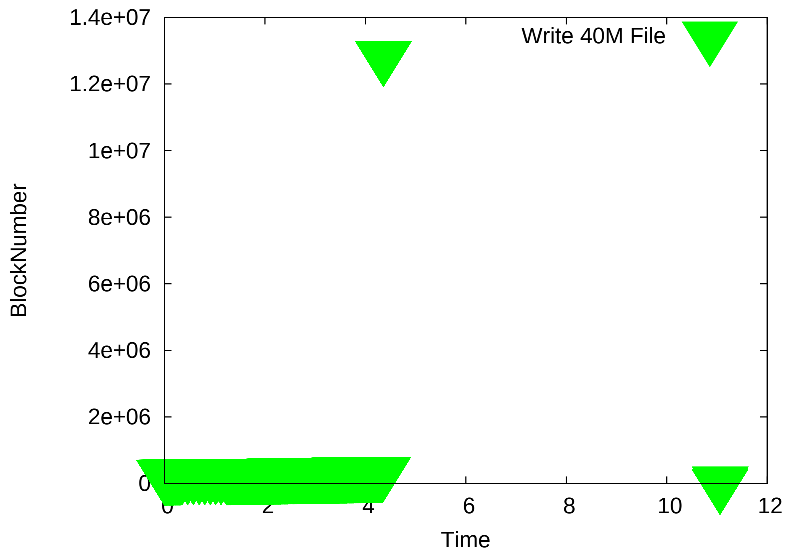
SD Card Characteristics

Card	Price/G	#AU	Page size	Erase Size
Kingston Class 10	$0.80	2	128k	4M
Toshiba Class 10	$1.20	2	64k	8M
SanDisk Extreme UHS-1	$5.00	9	64k	8M
SanDisk Ex-	$6.50	9	16k	4M

Write Patterns: File Create





(On Toshiba Exceria card)

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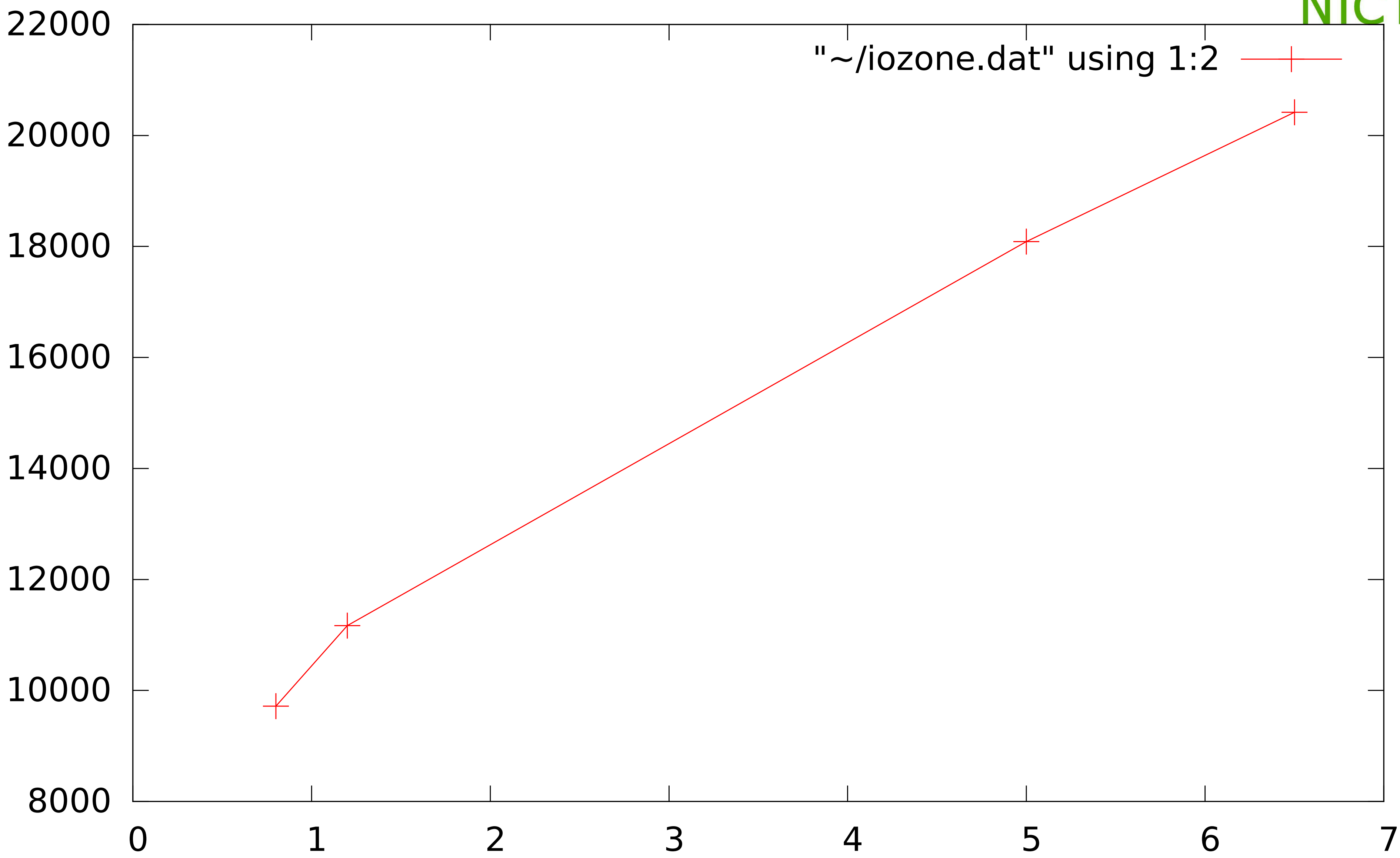

F2FS

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- Cooperate with garbage collection

F2FS

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- ‘Use on-card FTL, rather than work against it’
- Cooperate with garbage collection
- Use FAT32 optimisations

F2FS

- 2M Segments written as whole chunks

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NICTA

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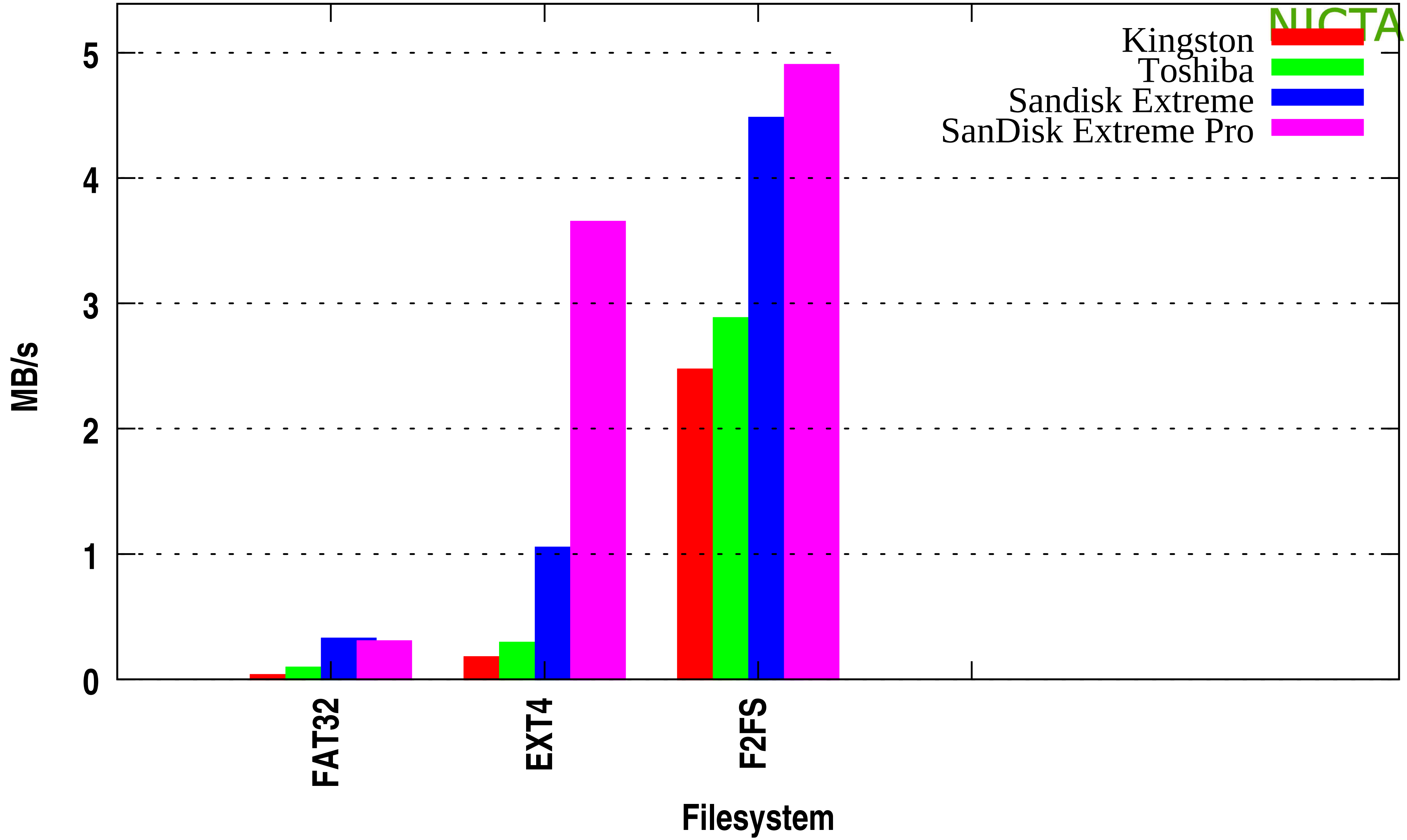
- 2M Segments written as whole chunks — always writes at log head
  — aligned with FLASH allocation units
- Log is the only data structure on-disk
- Metadata (e.g., head of log) written to FAT area in single-block writes
- Splits Hot and Cold data and Inodes.

BENCHMARKS: POSTMARK 32K READ



USING NON-F2FS

- Observation: XFS and ext4 already understand RAID

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USING NON-F2FS

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- Observation: XFS and ext4 already understand RAID
- RAID has multiple chunks, and a fixed stride, so...
- Configure FS as if for RAID

USING NON-F2FS

Still running benchmarks, see LCA talk next January for results!

NICTA

NICTA

The Multiprocessor Effect:

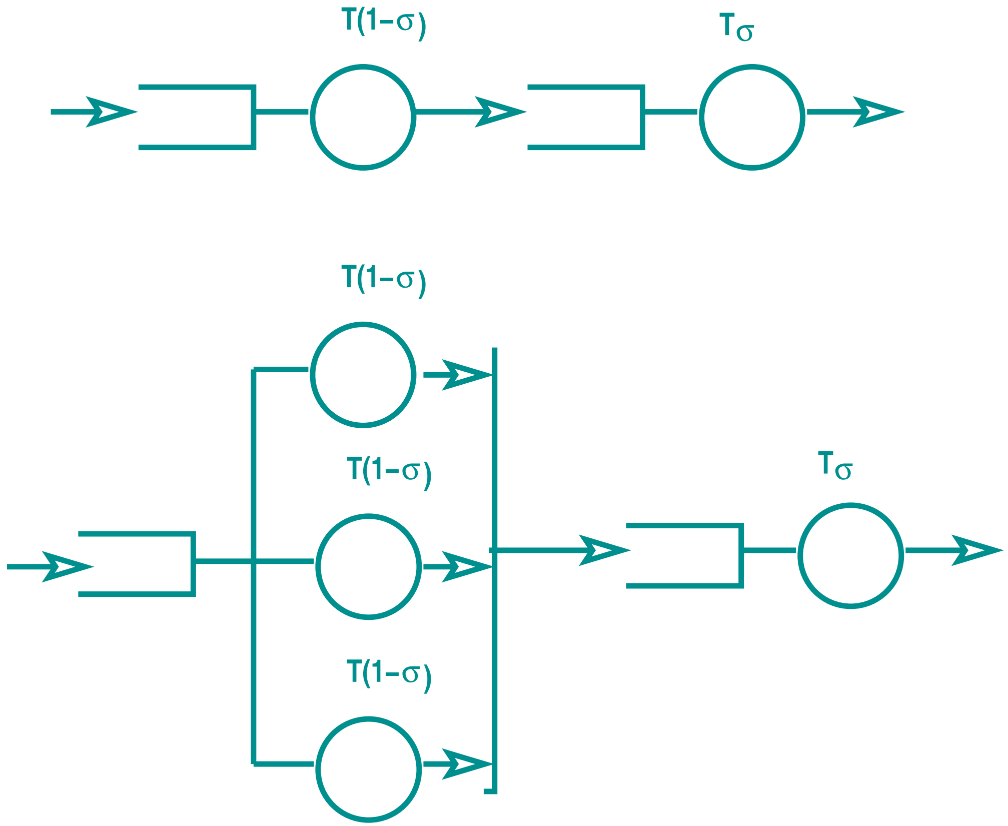
- Some fraction of the system's cycles are not available for application work:
  - Operating System Code Paths
  - Inter-Cache Coherency traffic
  - Memory Bus contention
  - Lock synchronisation
  - I/O serialisation

SCALABILITY

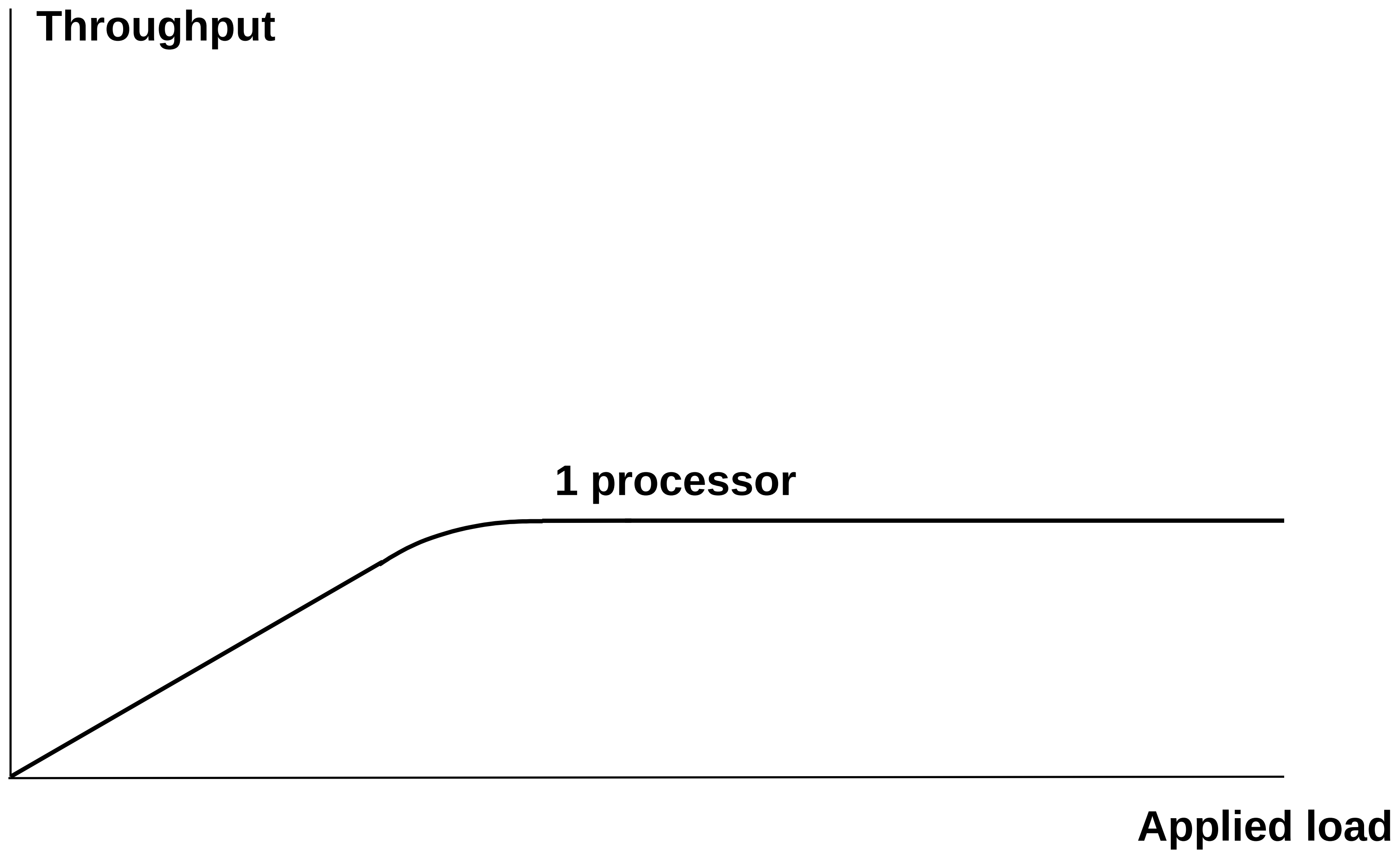
Amdahl's law:

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

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

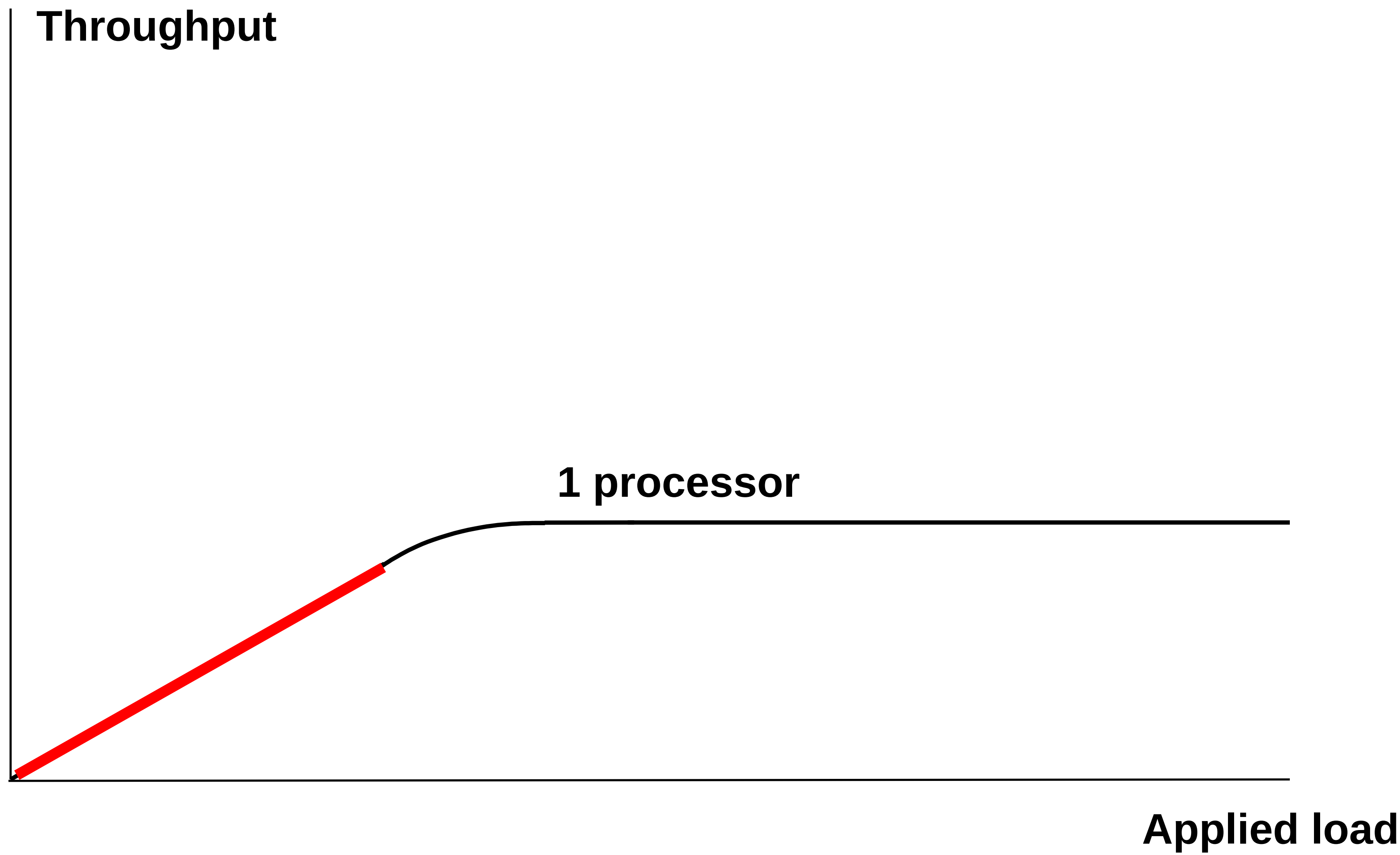


SCALABILITY

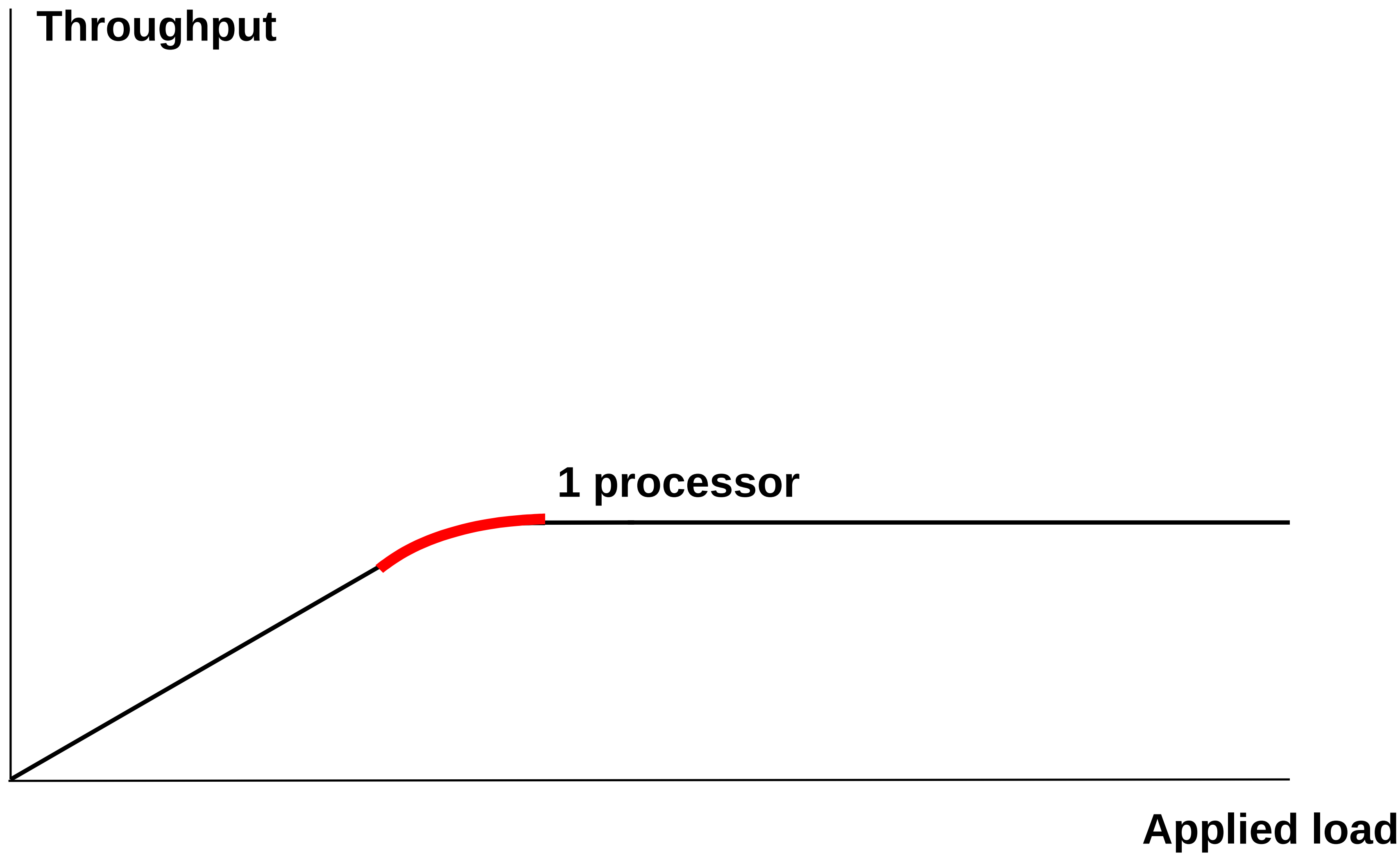


SCALABILITY

NICTA



SCALABILITY



SCALABILITY

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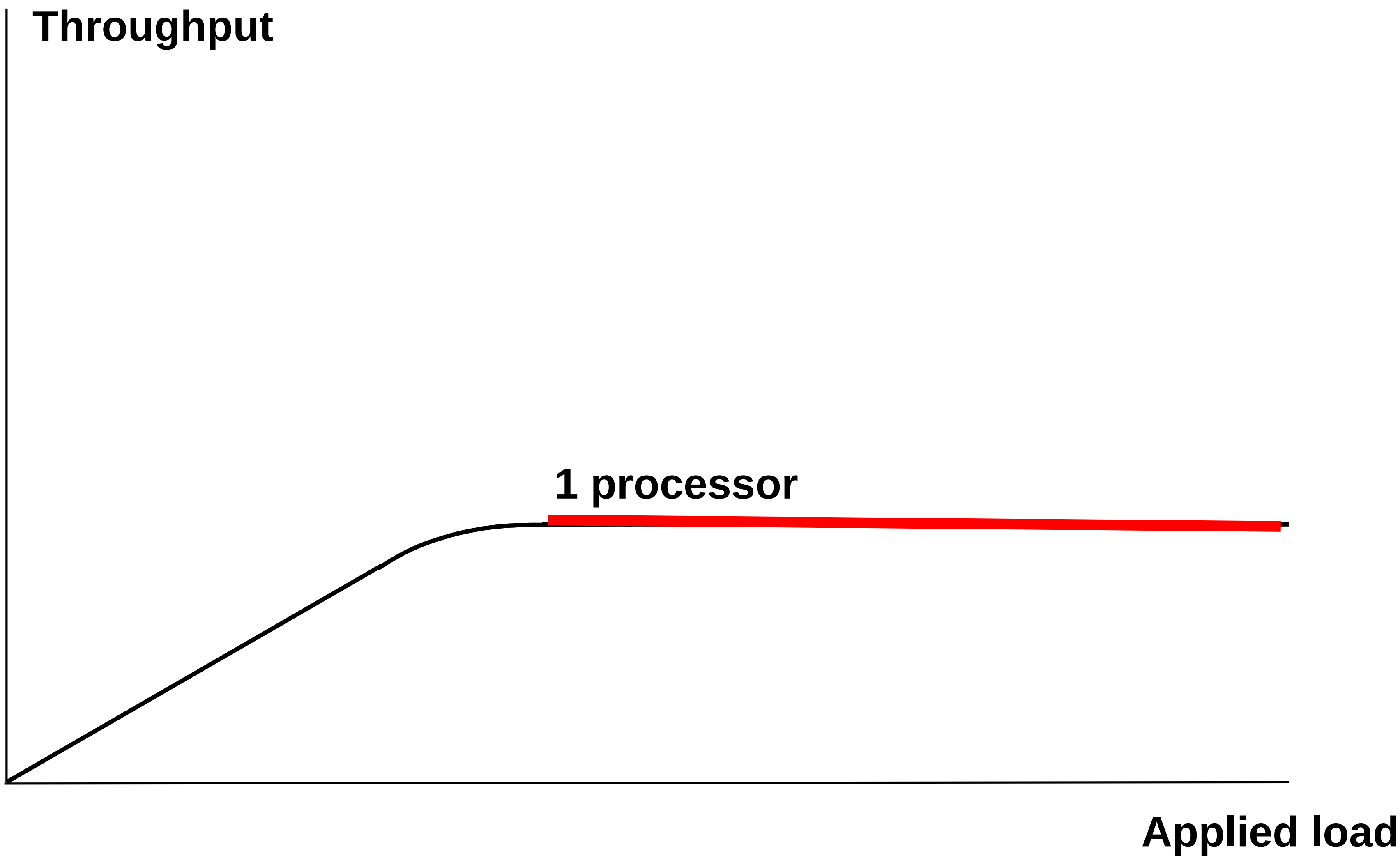

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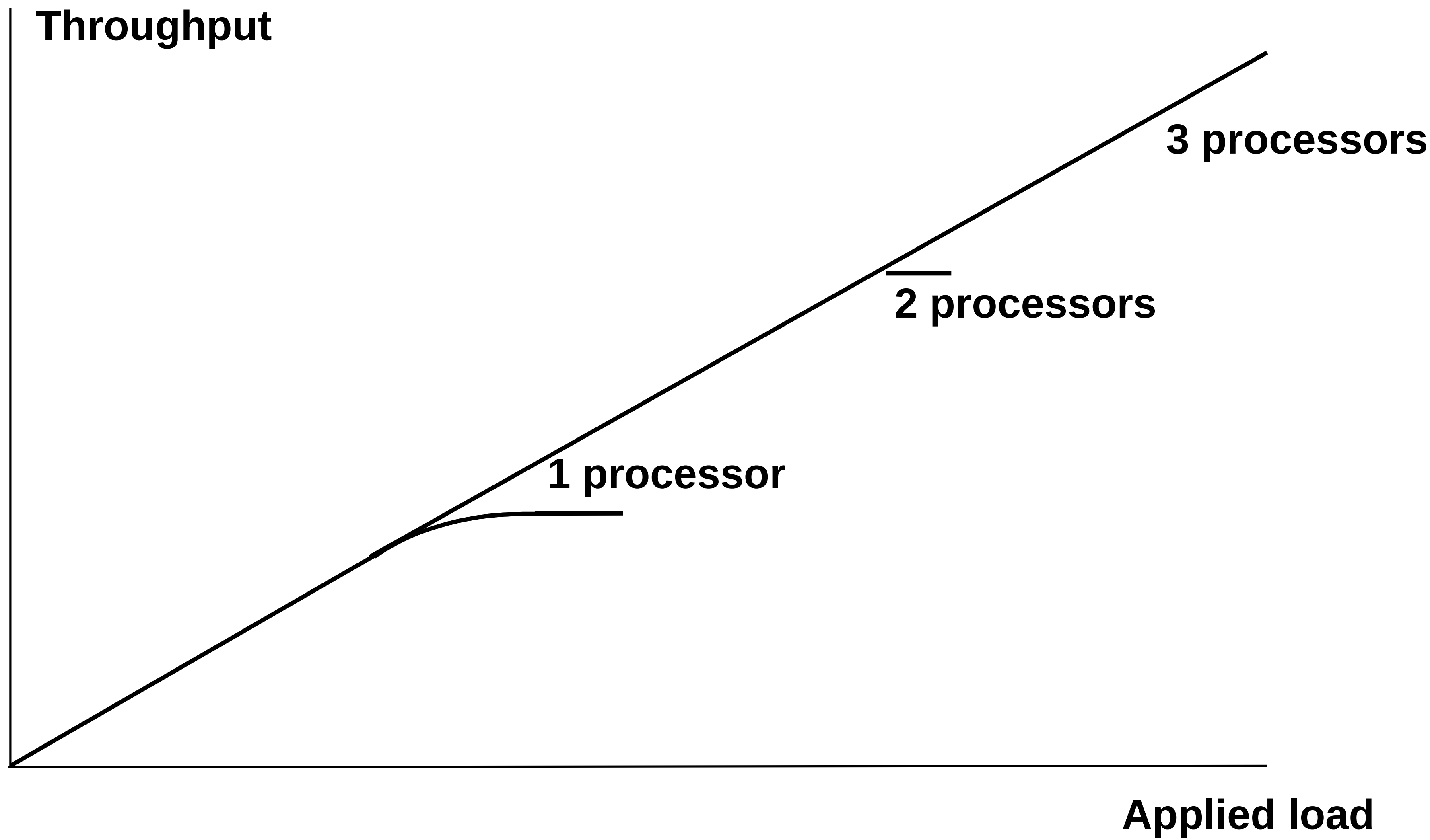

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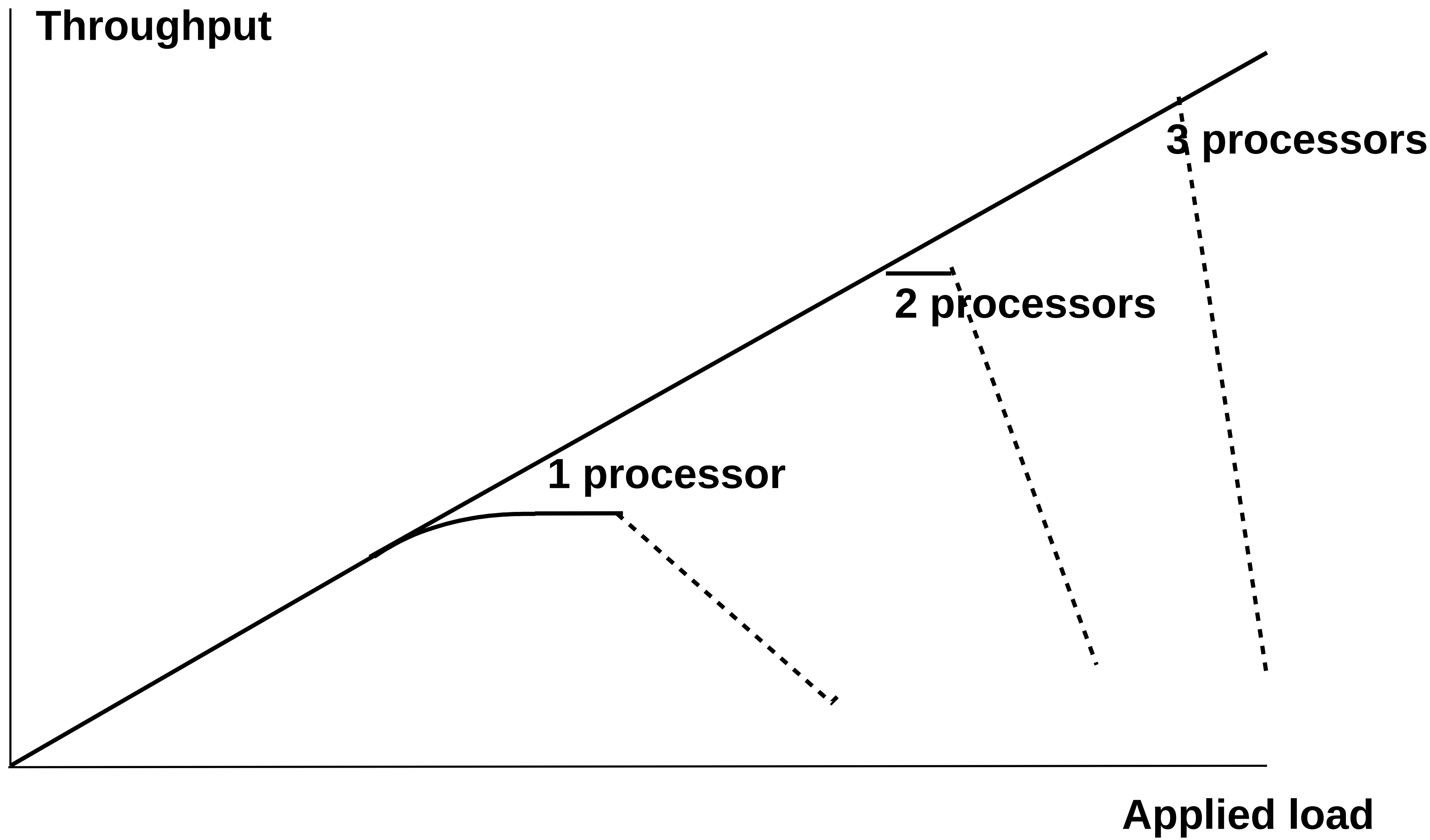

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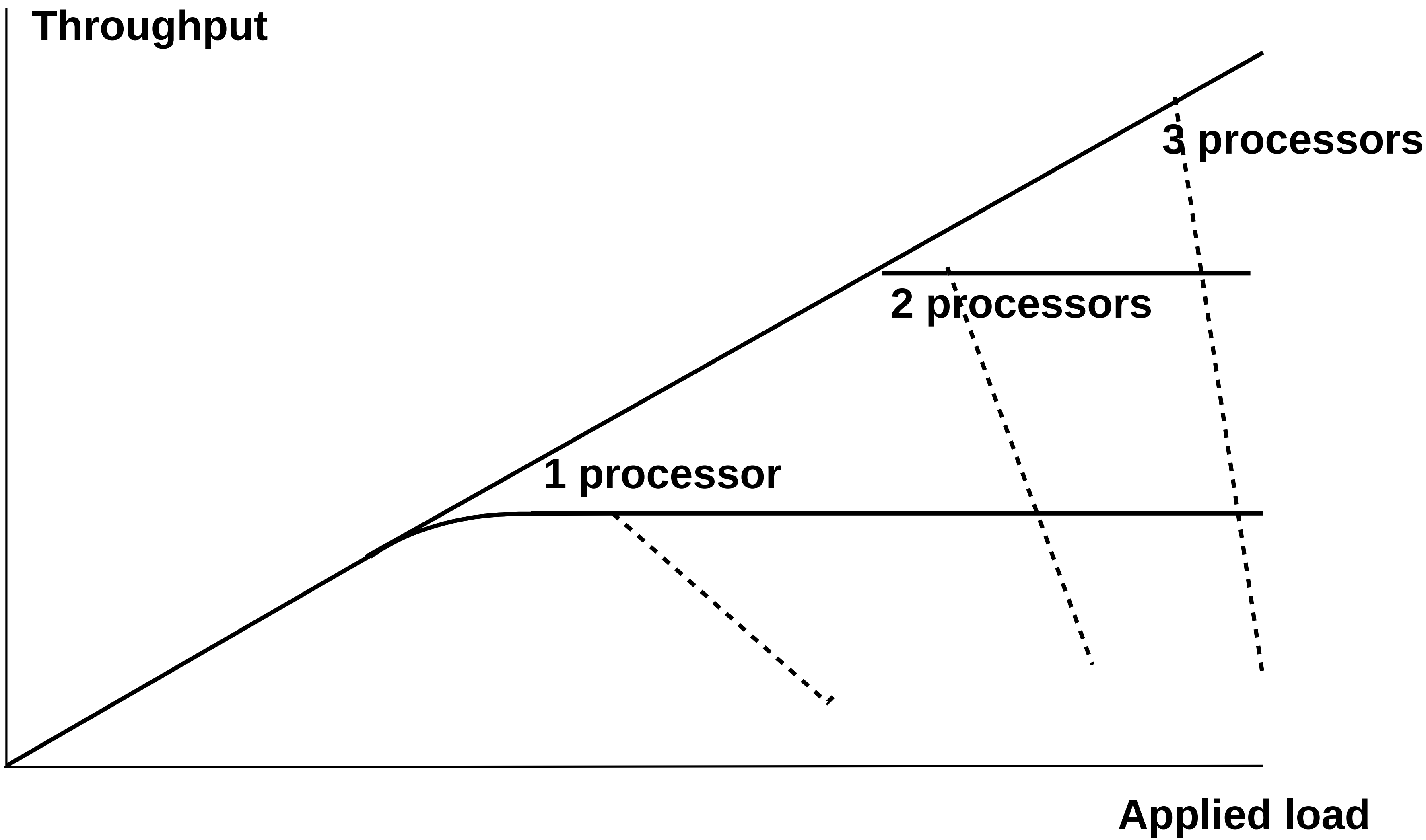
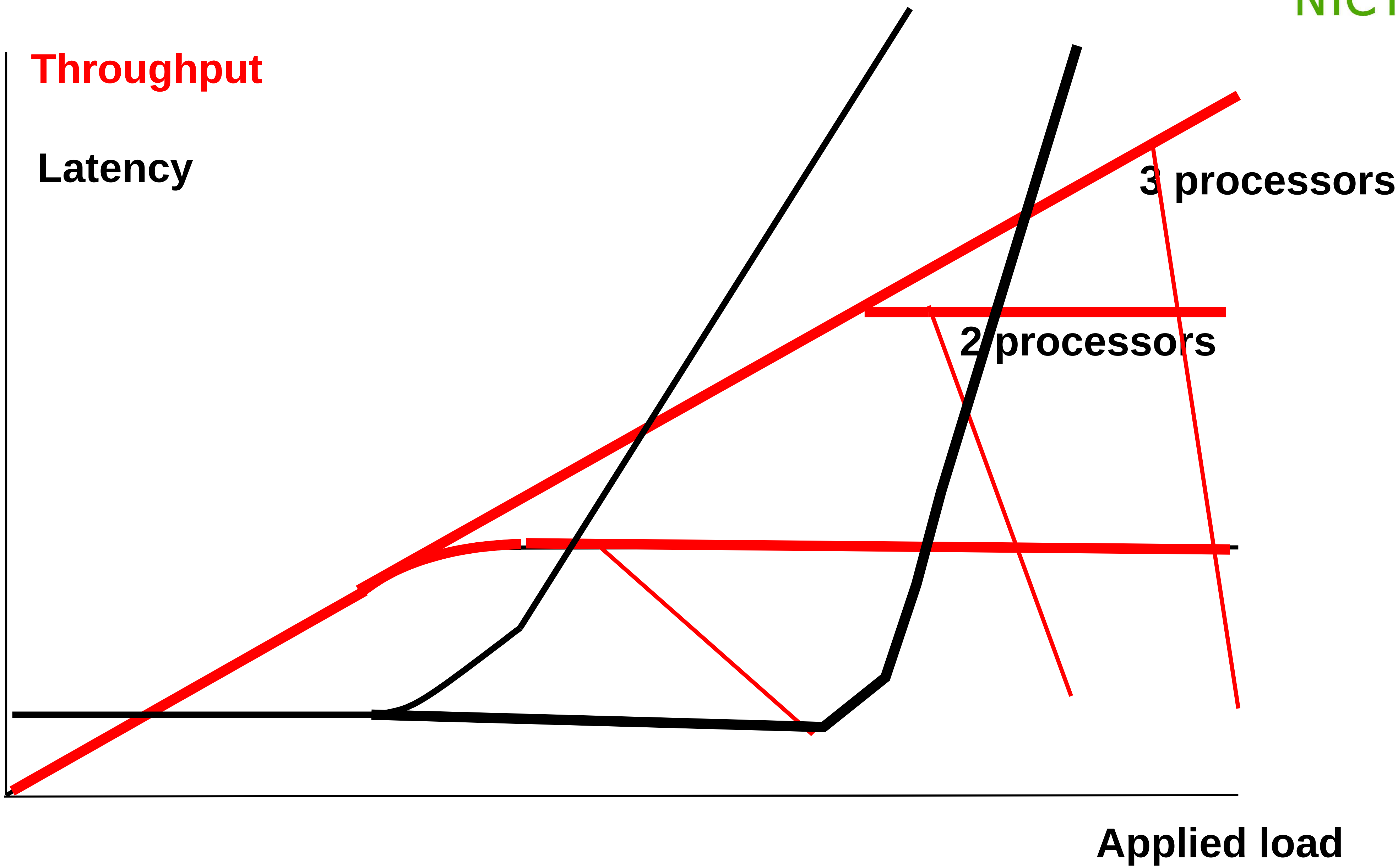


Scalability



Scalability

Gunther's law:

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

where:

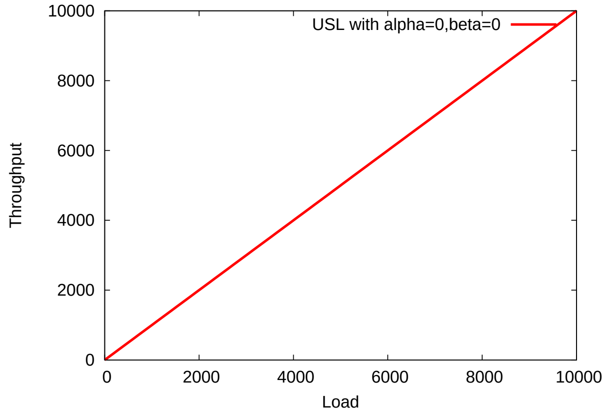
N is demand

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

β is the coherency delay in the system.

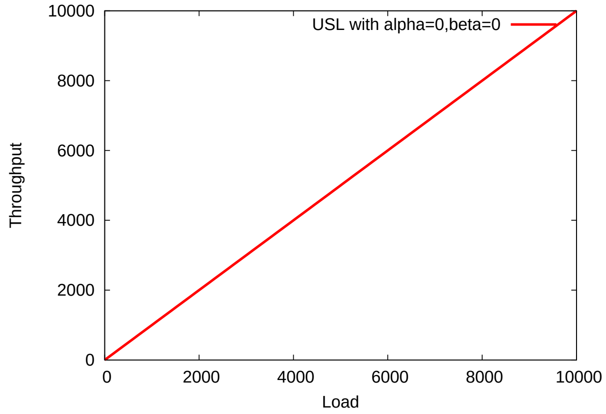
C is Capacity or Throughput

Scalability



$$\alpha = 0, \beta = 0$$

Scalability



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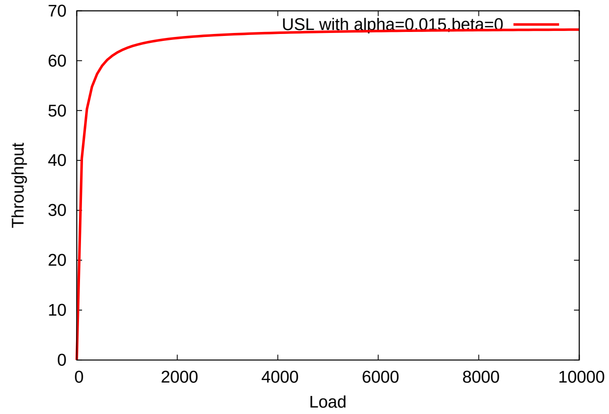
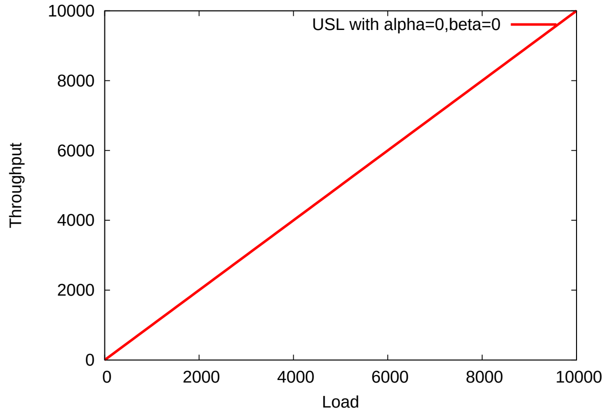


$$\alpha > 0, \beta = 0$$

Scalability



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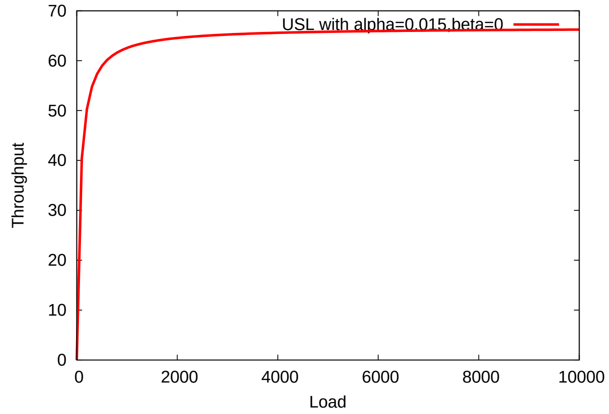
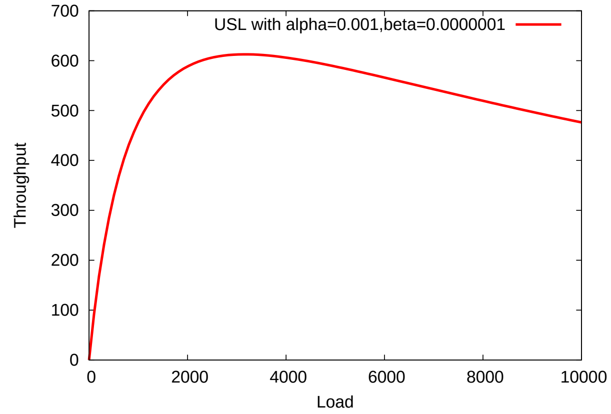


$$\alpha > 0, \beta = 0$$



$$\alpha > 0, \beta > 0$$

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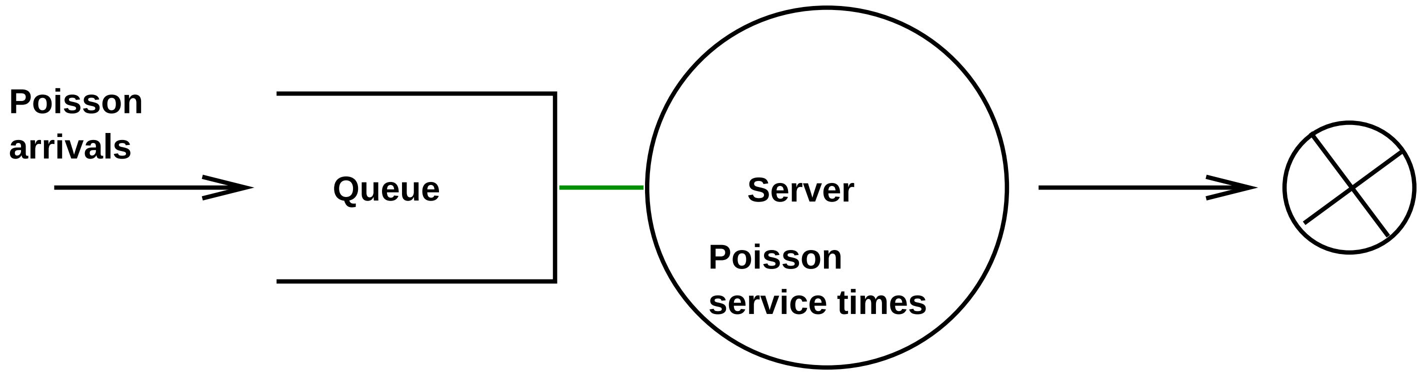
Queueing Models:



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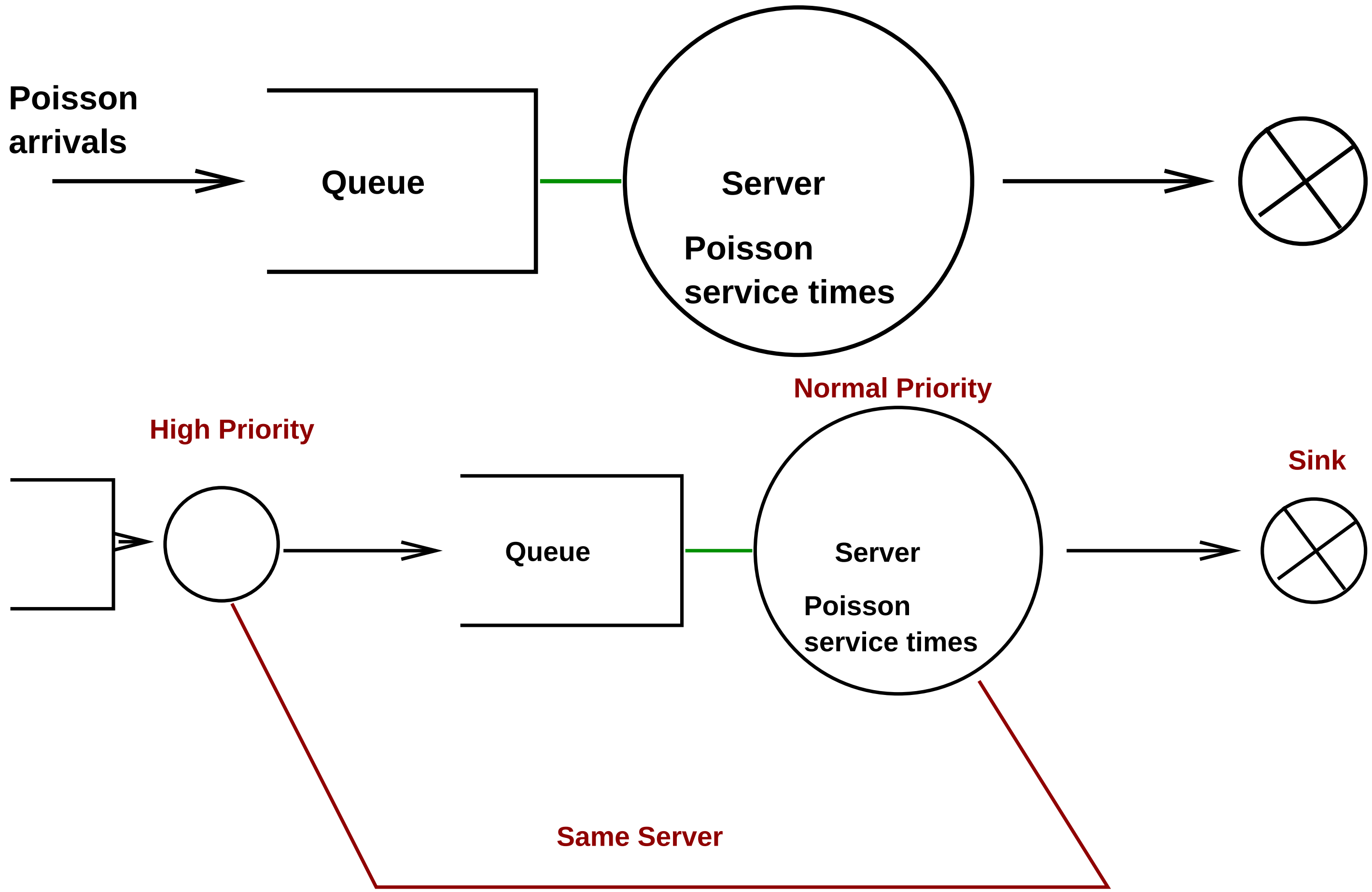
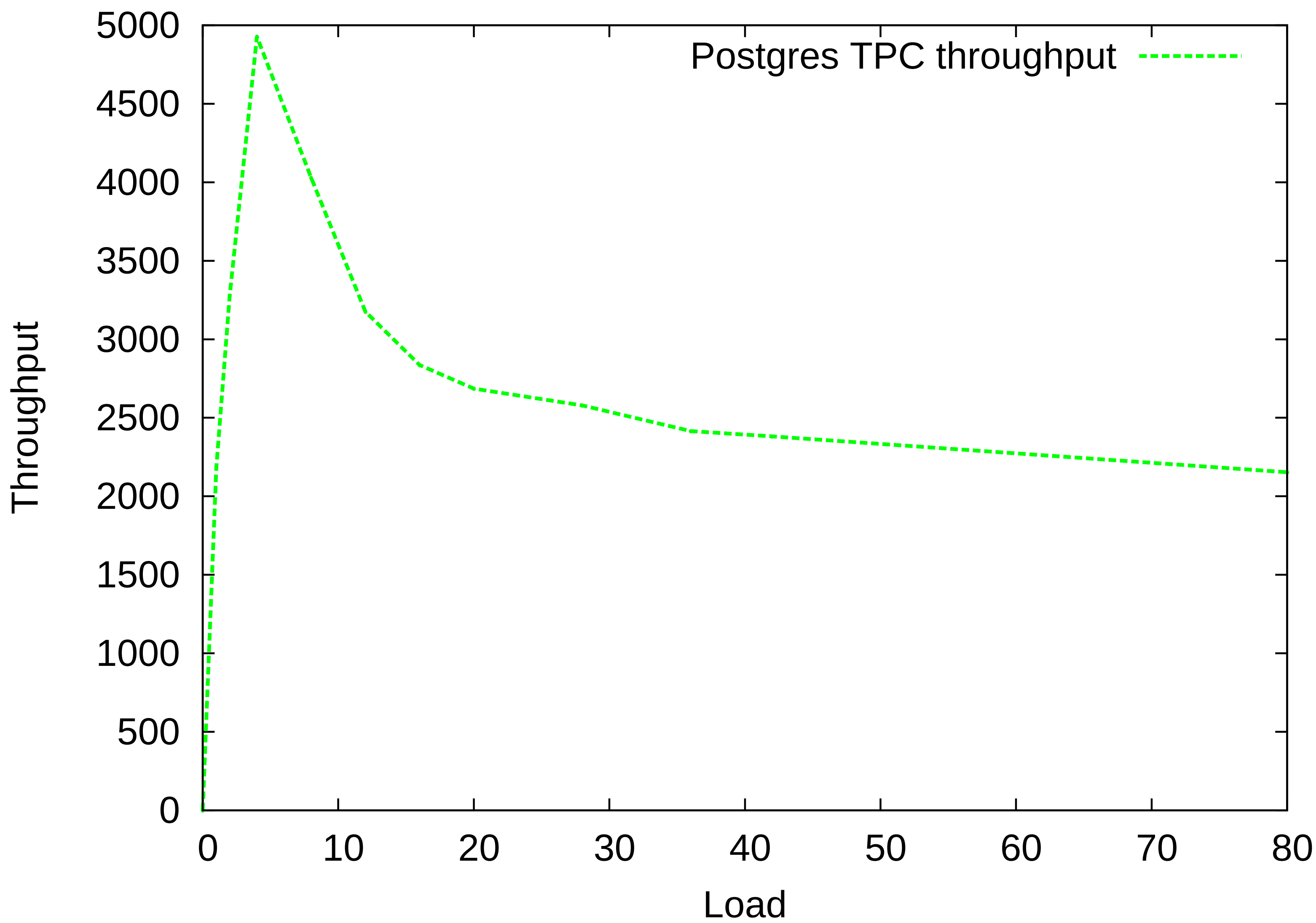
Queueing Models:



SCALABILITY

Real examples:



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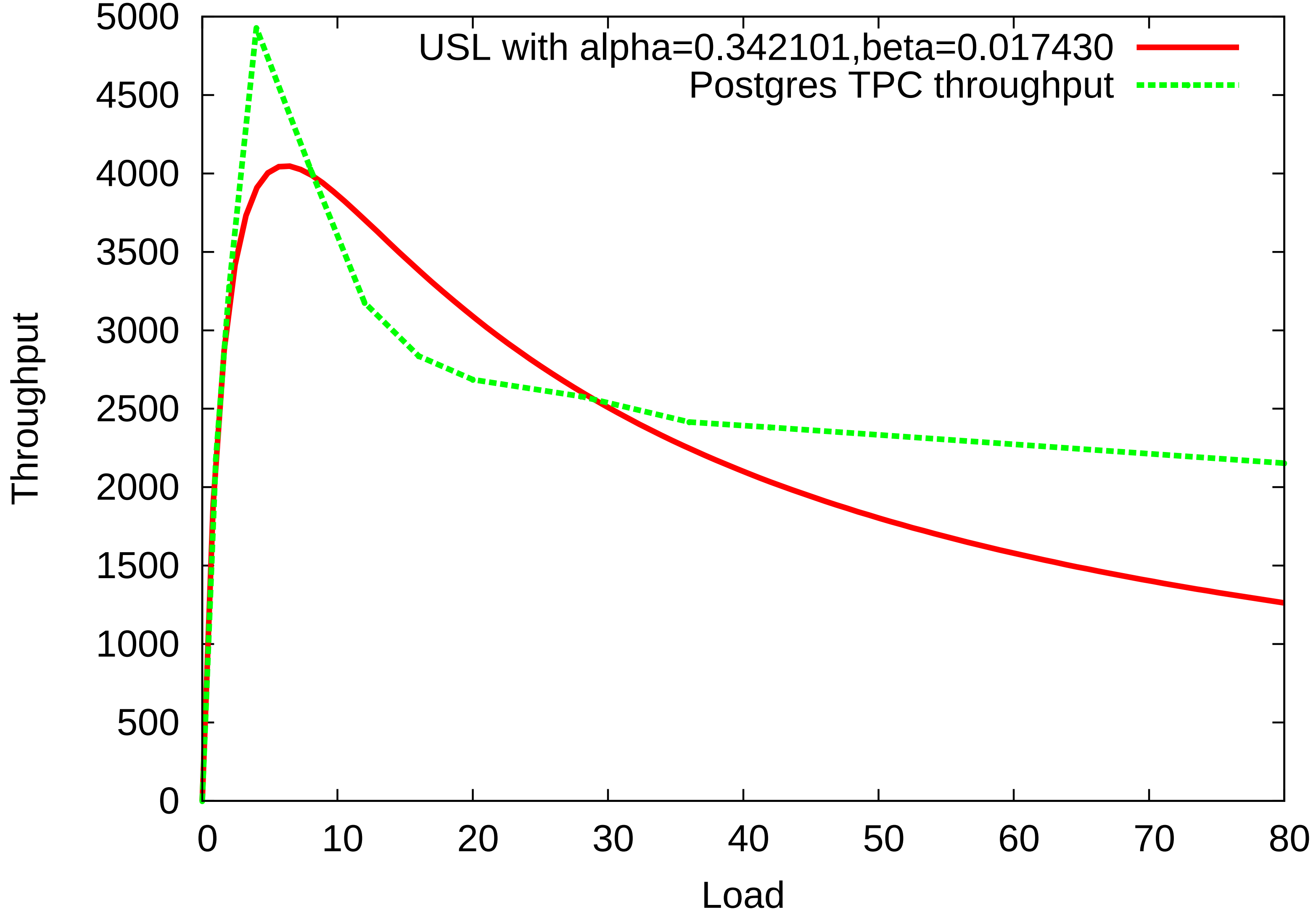
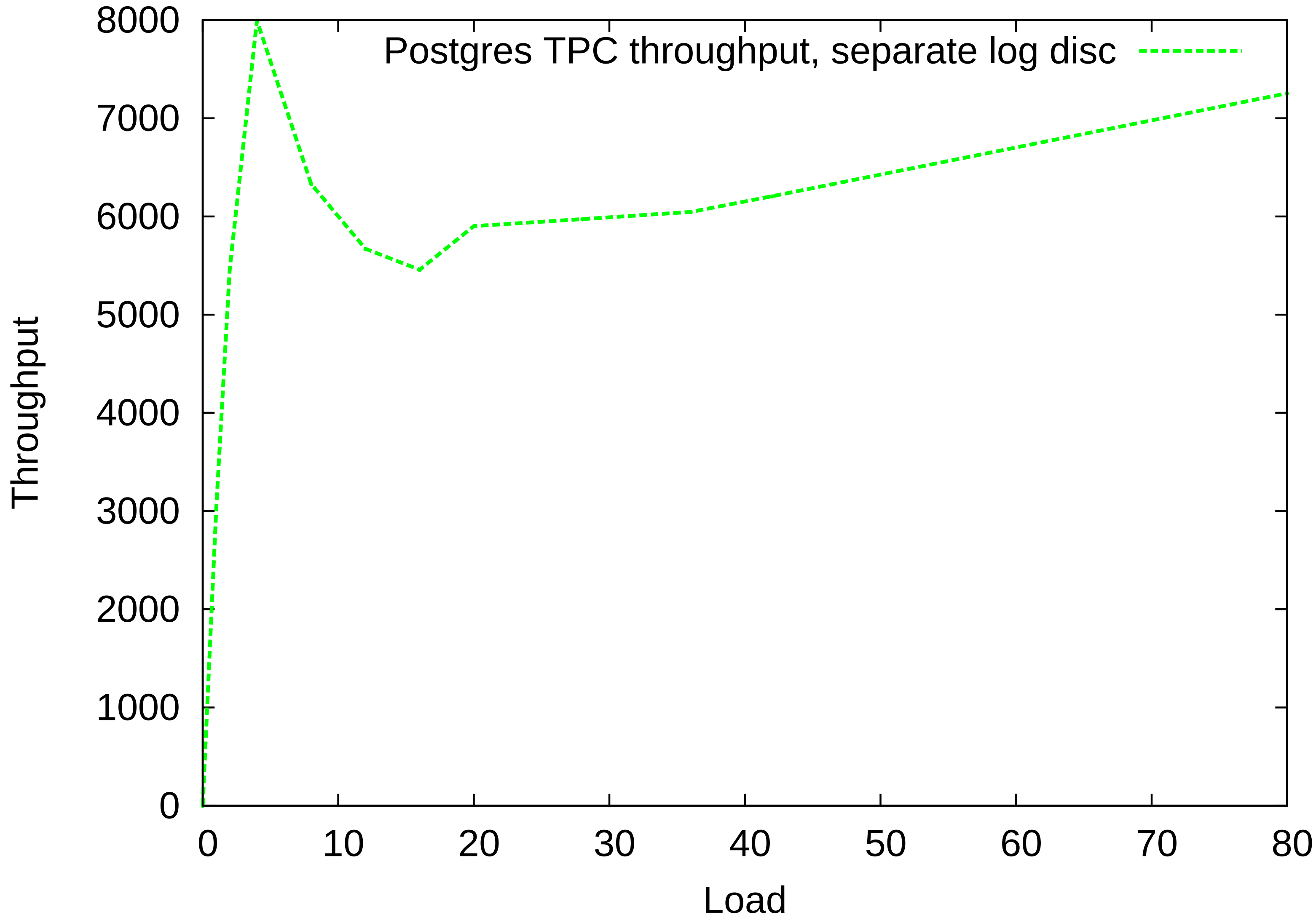
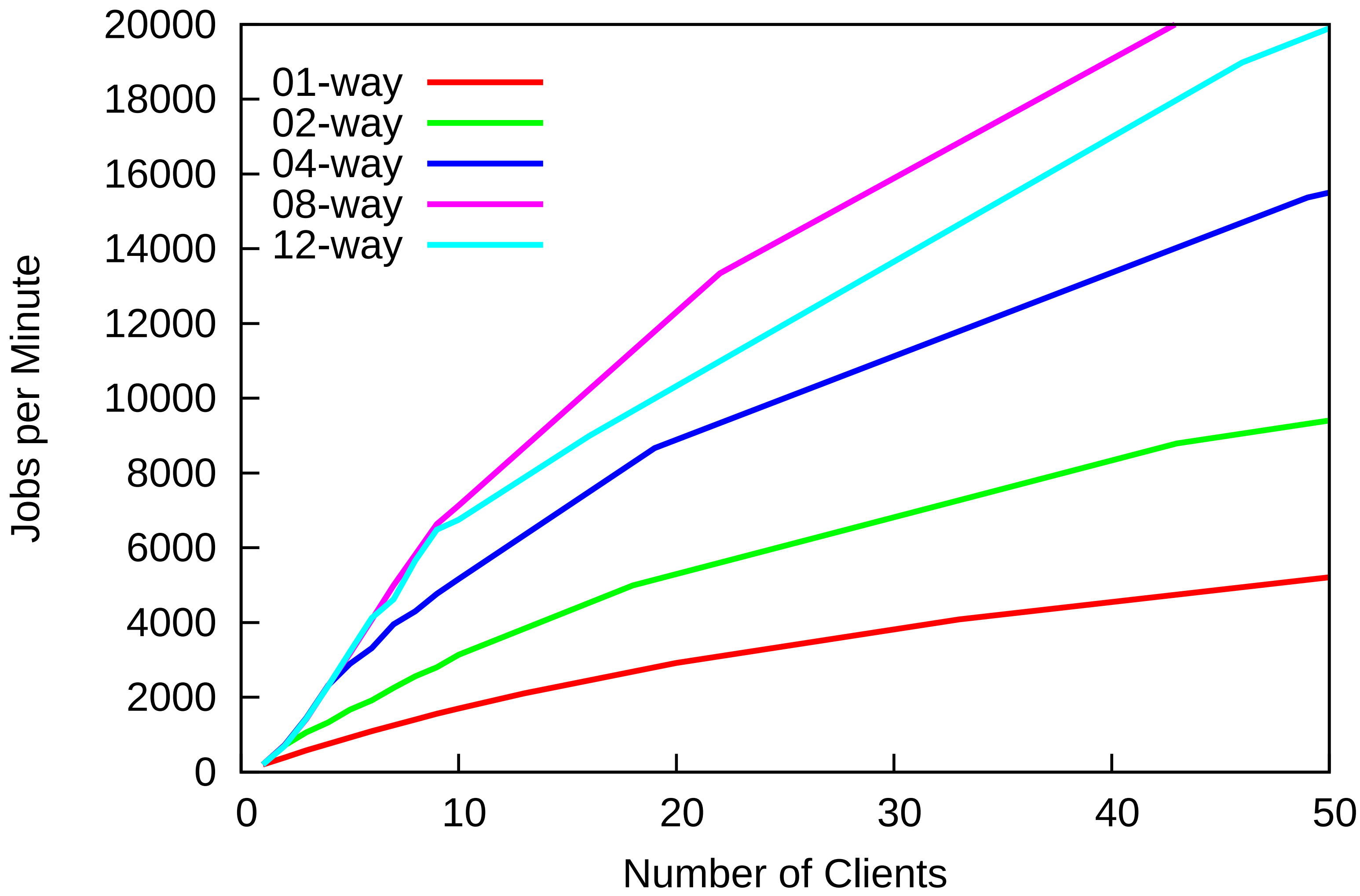


SCALABILITY



SCALABILITY

Another example:



SCALABILITY

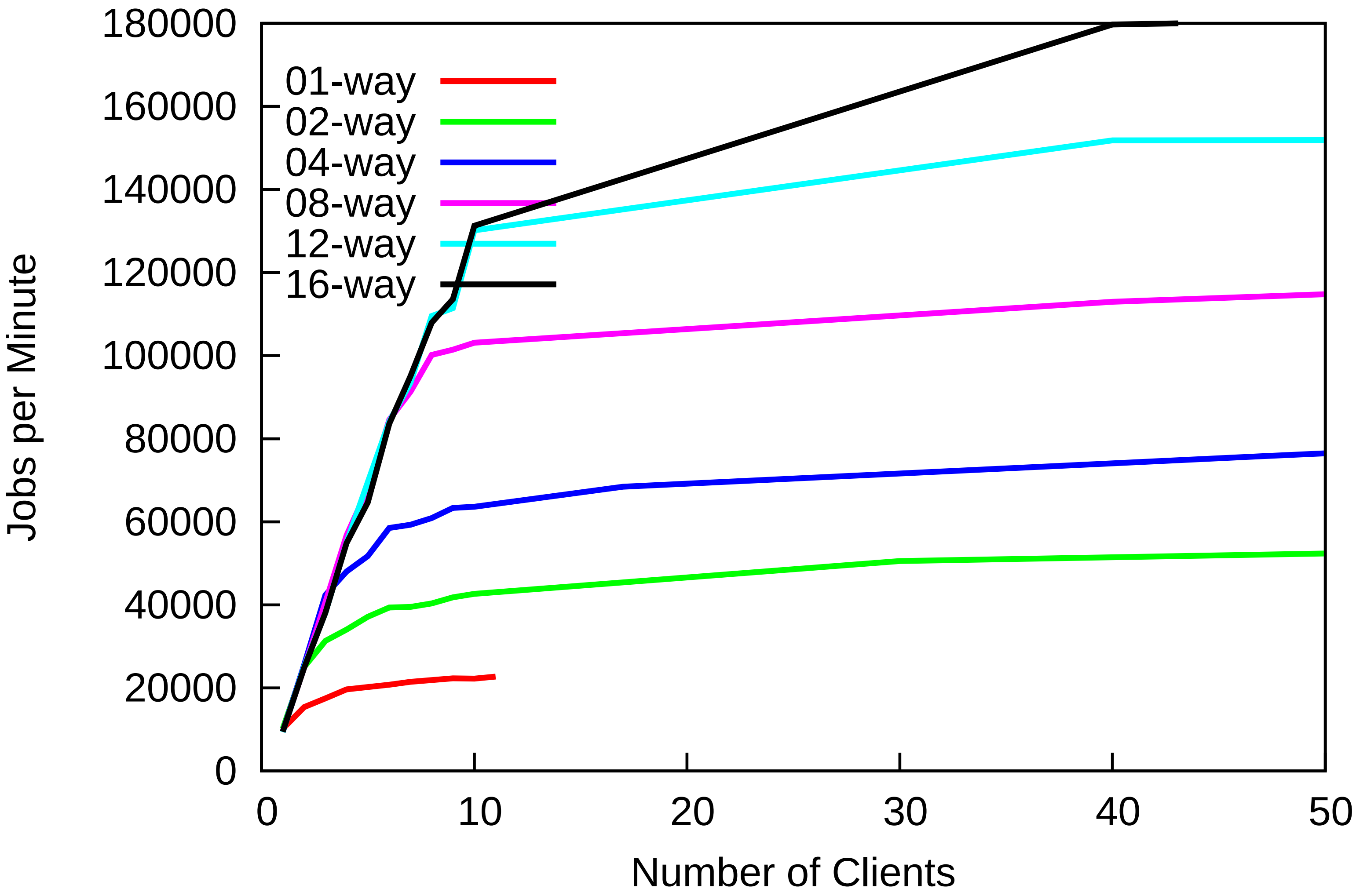
```
SPINLOCKS         HOLD          WAIT
UTIL   CON   MEAN( MAX )   MEAN( MAX )(% CPU)     TOTAL NOWAIT SPIN RJECT  NAME

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

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- Find the bottleneck
  - not always easy

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Tackling scalability problems

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TACKLING SCALABILITY PROBLEMS

- Find the bottleneck
- fix or work around it
- check performance doesn't suffer too much on the low end.
- Experiment with different algorithms, parameters

Tackling scalability problems

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- Each solved problem uncovers another
- Fixing performance for one workload can worsen another

TACKLING SCALABILITY PROBLEMS

- Each solved problem uncovers another
- Fixing performance for one workload can worsen another
- Performance problems can make you cry

DOING WITHOUT LOCKS

Avoiding Serialisation:

- *Lock-free* algorithms
- Allow safe concurrent access *without excessive serialisation*

DOING WITHOUT LOCKS

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();
    ....
} while (lastseq != seq);
```

DOING WITHOUT LOCKS

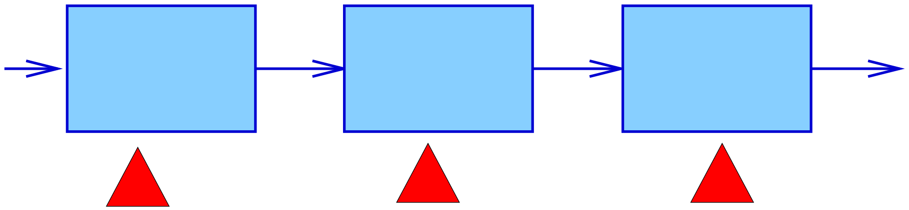
Writer:

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

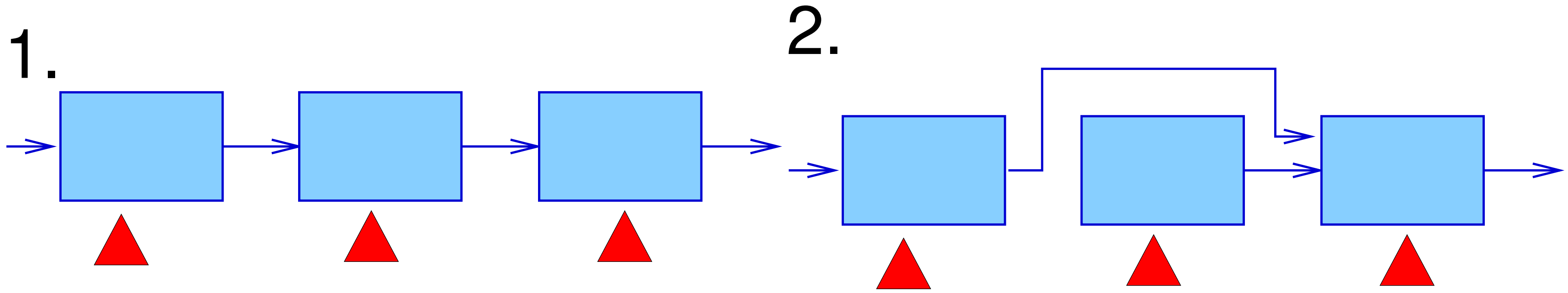
DOING WITHOUT LOCKS

RCU: ??

1.

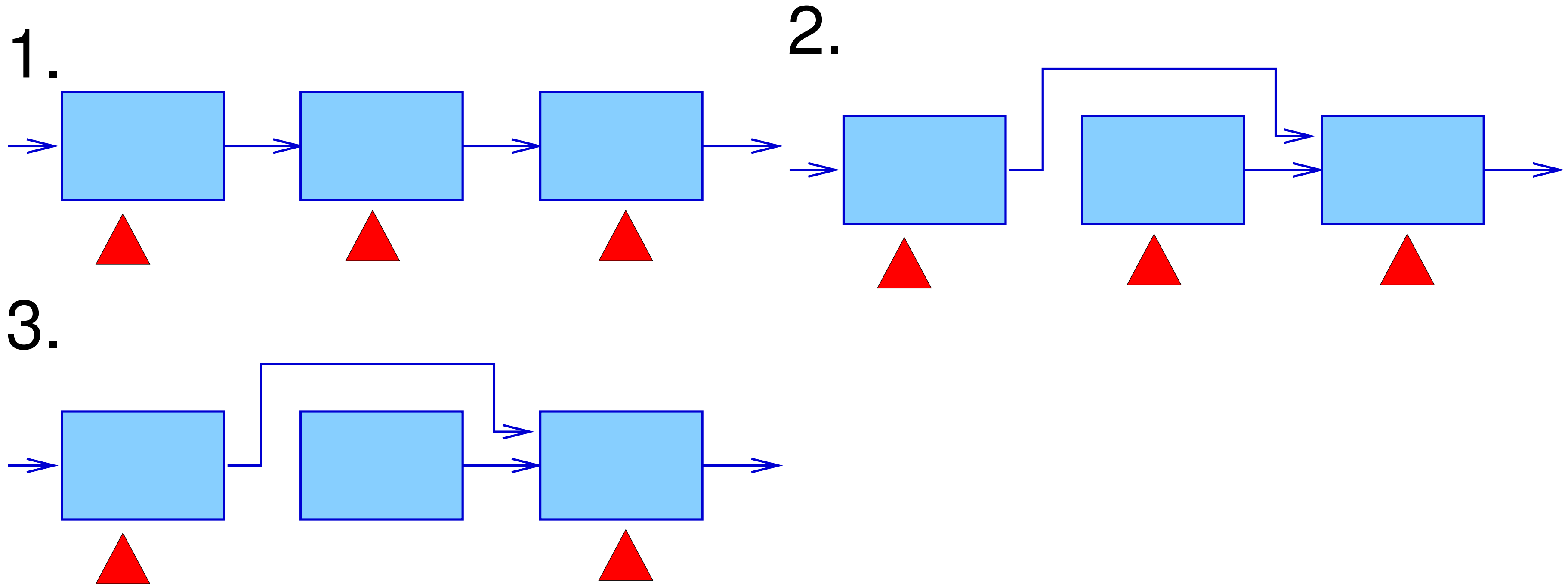


RCU: **??**



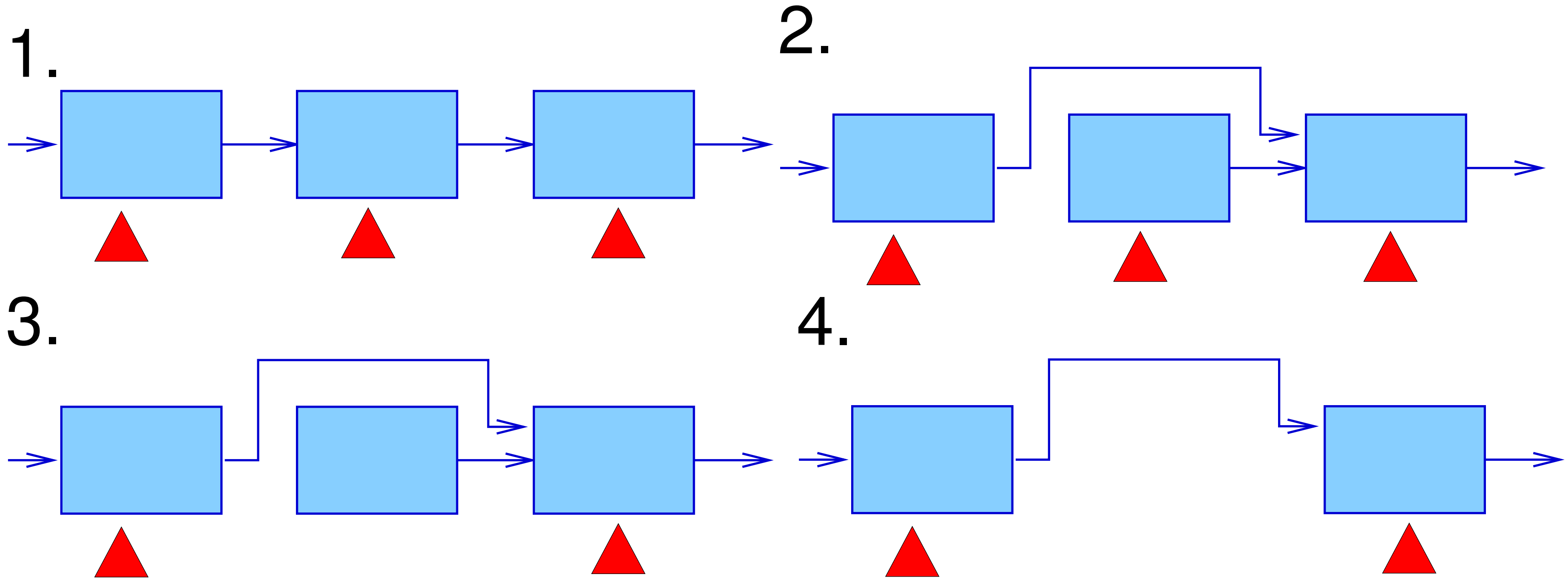
DOING WITHOUT LOCKS

RCU: **??**



DOING WITHOUT LOCKS

RCU: **??**



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McKenney, P. E., Sarma, D., Arcangelli, A., Kleen, A., Krieger, O. & Russell, R. (2002), Read copy update, *in*

BACKGROUND READING

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'Ottawa Linux Symp.'.

URL:

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