Linux, Locking and Lots of Processors

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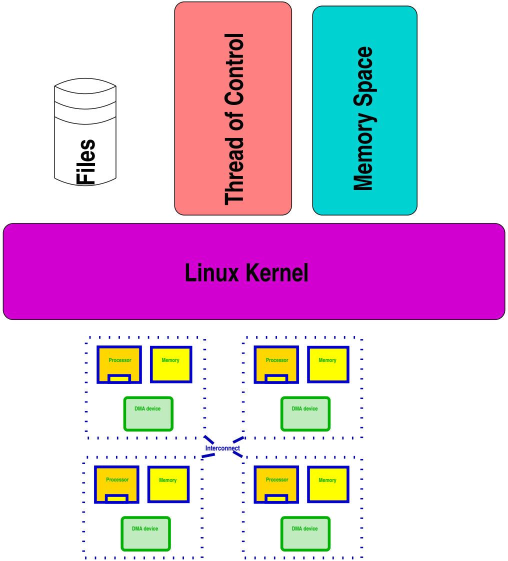
- Additions:
  - Paged virtual memory (3BSD, 1979)
  - TCP/IP Networking (BSD 4.1, 1983)
  - Multiprocessing (Vendor Unices such as Sequent's 'Balance', 1984)

Abstractions

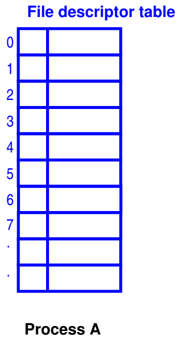


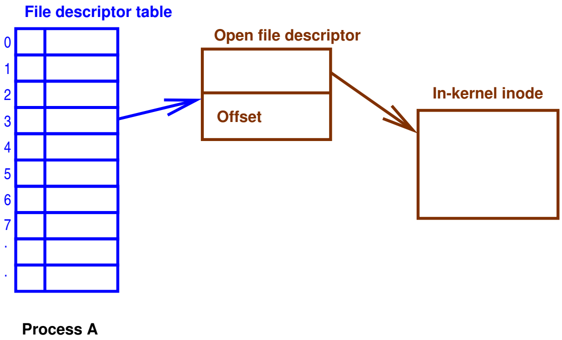
Process model

- 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
- 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


File descriptor table
0
1
2
3
4
5
6
7
.
.
Process A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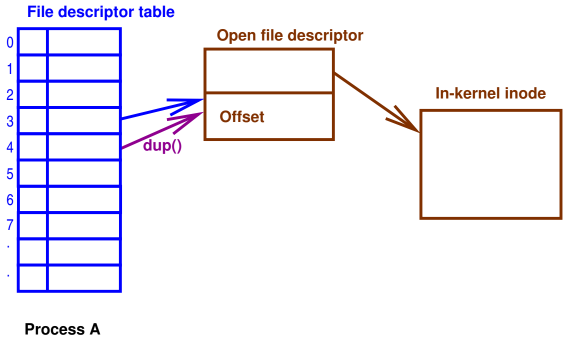
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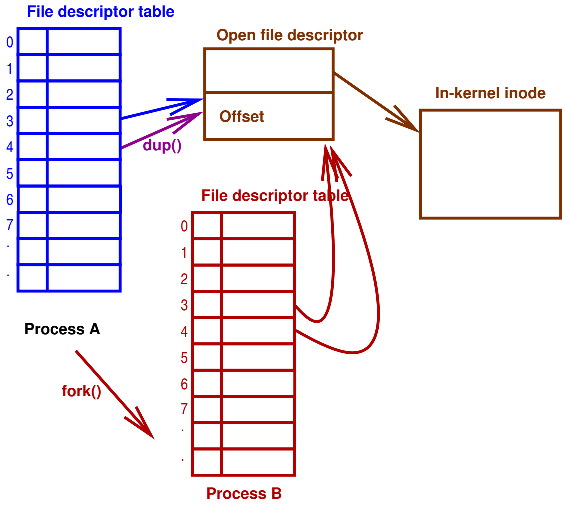
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Process A
fork()
File descriptor table
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.
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Process B


```
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
- 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

— Processes are proxies for authenticated real people
— UID, GID, Other — `rwx`
— Mainly for File access.
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— UID, GID, Other — `rwx`

— Mainly for File access.

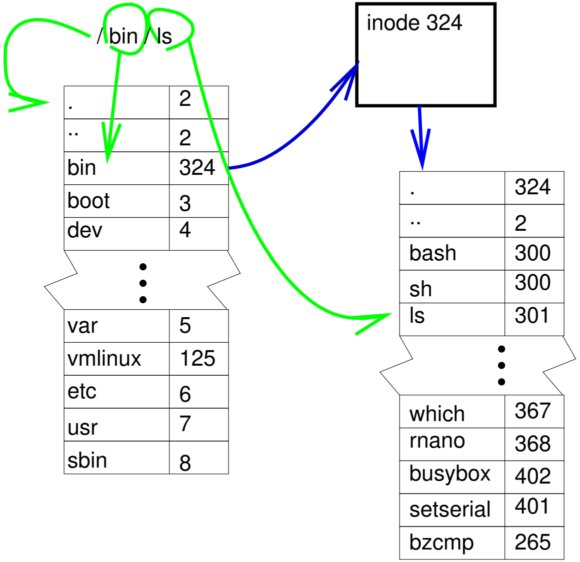
— A process can signal any other process with the same UID

— A process with UID 0 can signal any process, operate on any file*

* Conditions apply

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.


/ 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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- Can be slow: extensive use of caches to speed it up *dentry cache* — becomes SMP bottleneck
- hide filesystem and device boundaries
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Evolution

KISS

— Simplest possible algorithm used at first

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  - Easy to show correctness
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- 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`

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

- 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

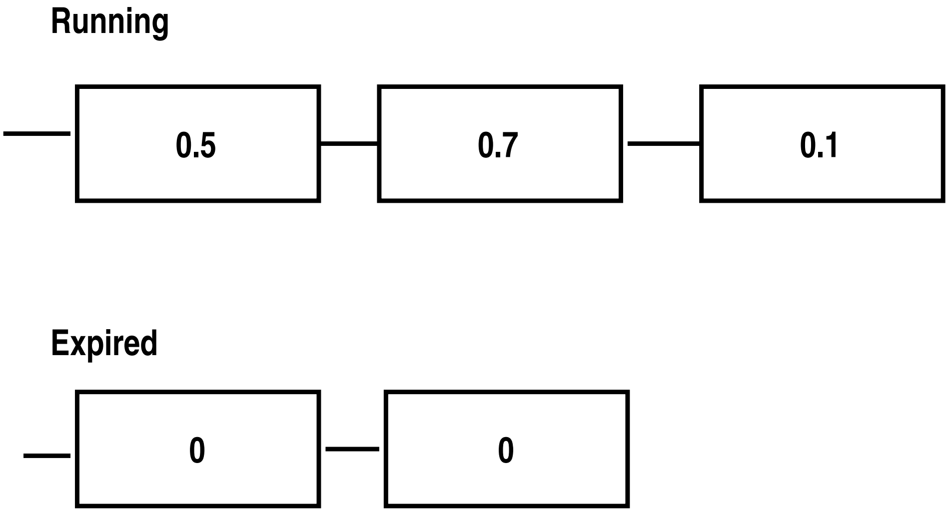
Scheduling

Goals

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

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

Dual Entitlement Scheduler



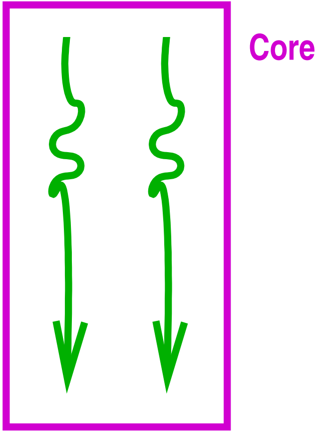
CFS

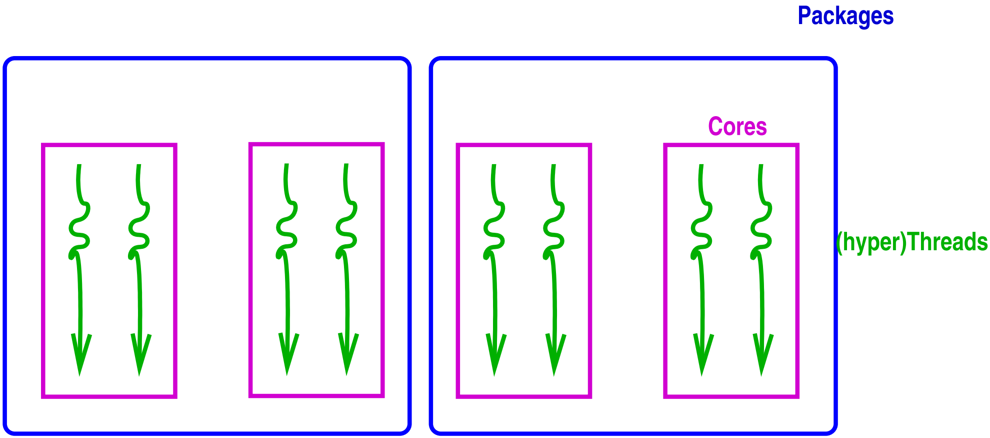
1. Keep tasks ordered by effective CPU runtime weighted by nice in red-black tree
2. Always run left-most task.

Devil's in the details:

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

(hyper)Thread


Core


Packages
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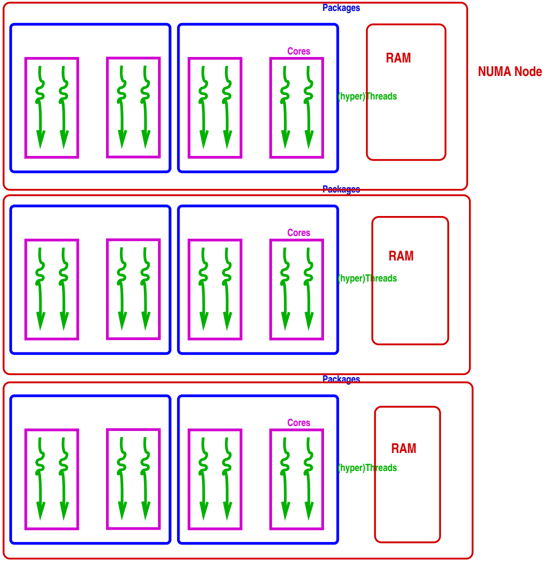
Packages
Cores
RAM
(hyper)Threads
NUMA Node
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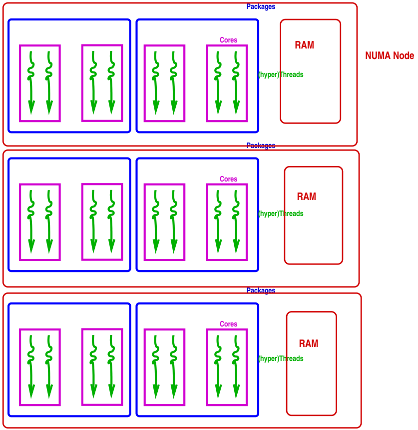
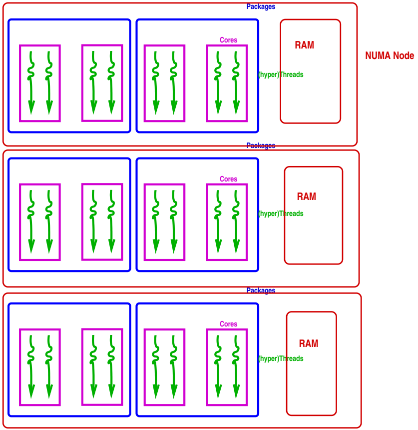


— Best to reschedule on same processor (don't move cache footprint, keep memory close)



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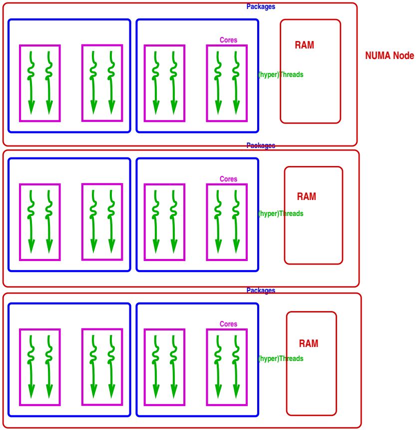

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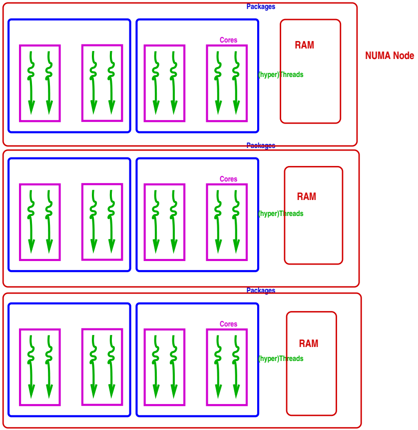
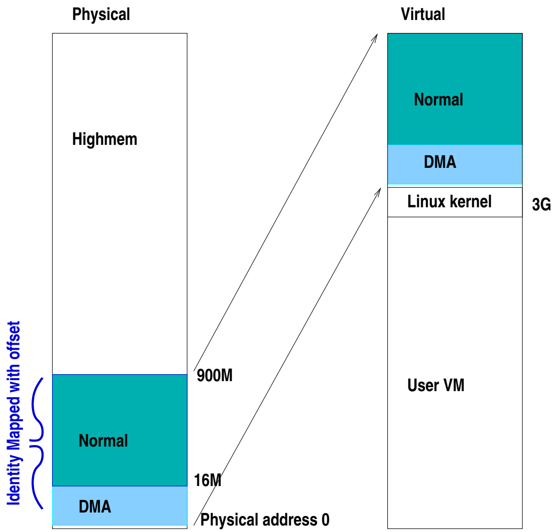


- Best to reschedule on same processor (don’t move cache footprint, keep memory close)
  - Otherwise schedule on a ‘nearby’ processor
- Try to keep whole sockets idle (can power them off)
- Somehow identify cooperating threads, co-schedule ‘close by’?

- 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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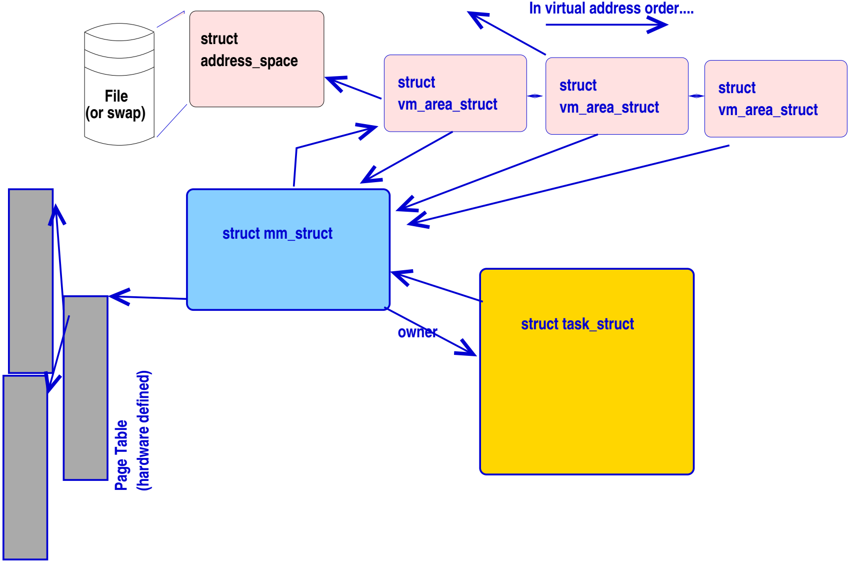
- More memory: change kernel to refer to memory by `struct page`

- 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:

A enumerable-bus device

B Non-enumerable-bus device

Driver Interface: Device Discovery

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

Device Tree

— Describe board+peripherals

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  - replaces ACPI on embedded systems

Device Tree

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  - replaces ACPI on embedded systems
- Names in device tree trigger driver instantiation

```
uart_A: serial@84c0
        compatible = "amlogic,meson6-uart", "amlogic,meson-uar
        reg = <0x84c0 0x18>;
        interrupts = <GIC_SPI 26 IRQ_TYPE_EDGE_RISING>;
        status = "okay";
;
```

Debugging device discovery

Add `debug_initcalls` to Linux boot args

— traces all calls to `init()` functions at boot time.

(See `Documentation/admin-guide/kernel-parameters.txt` in the linux kernel source for other useful boot args)

Containers

— *Namespace* isolation

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In hierarchy of control groups

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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

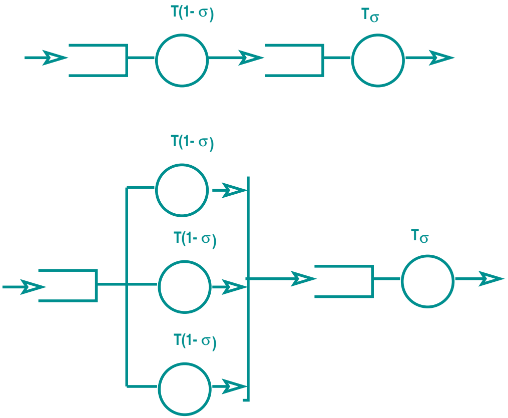
Scalability

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

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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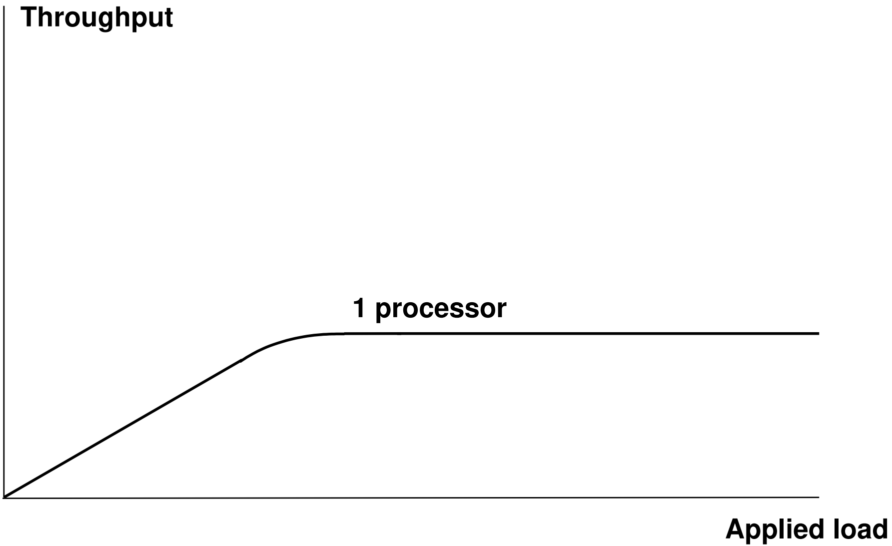

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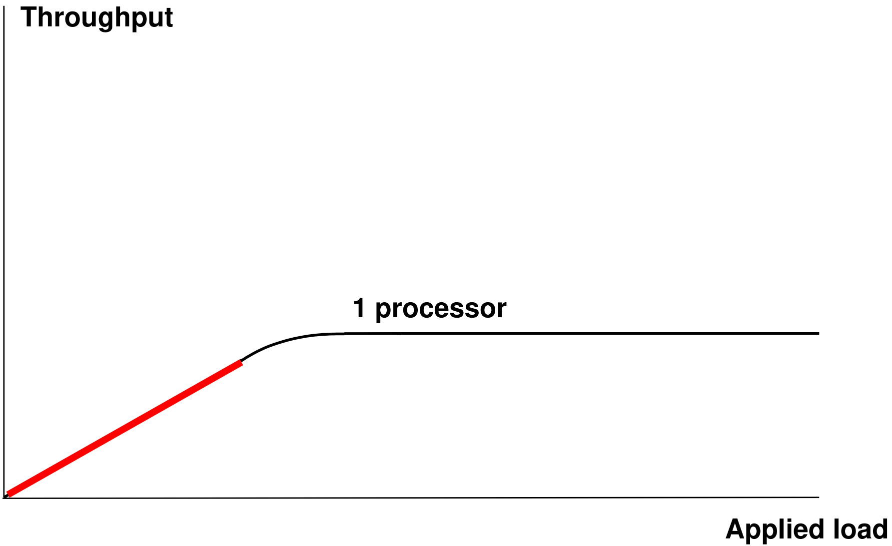

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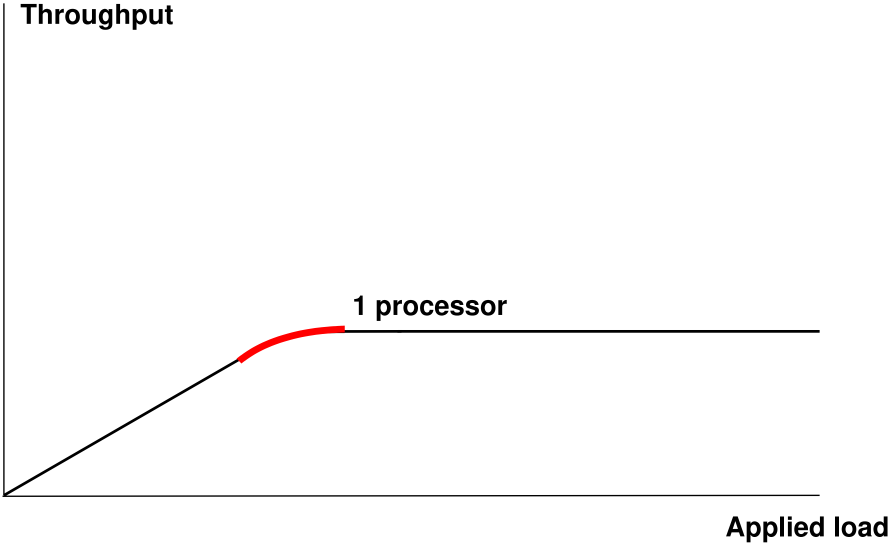

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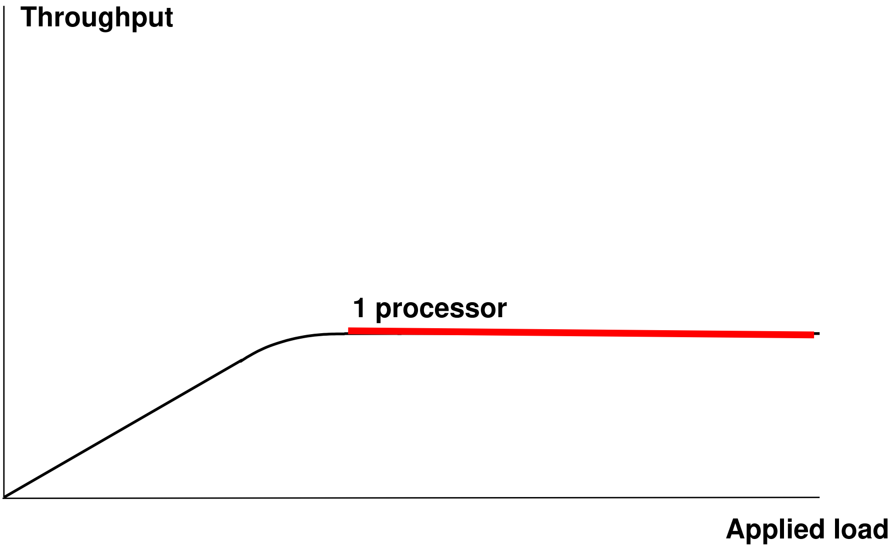

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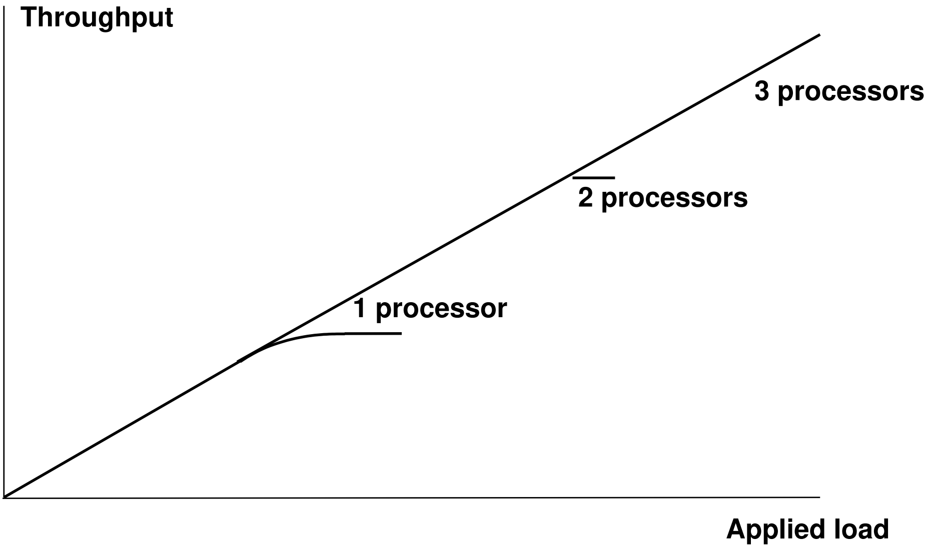

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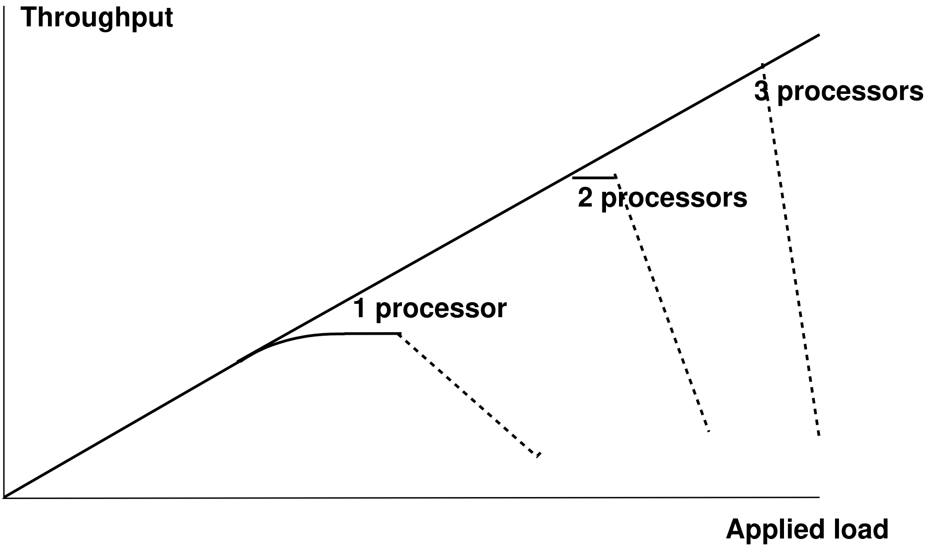

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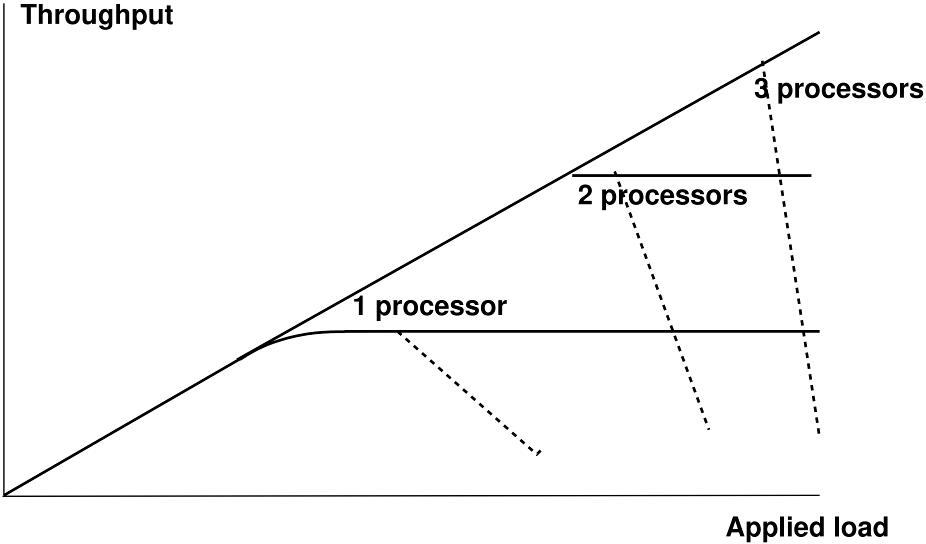

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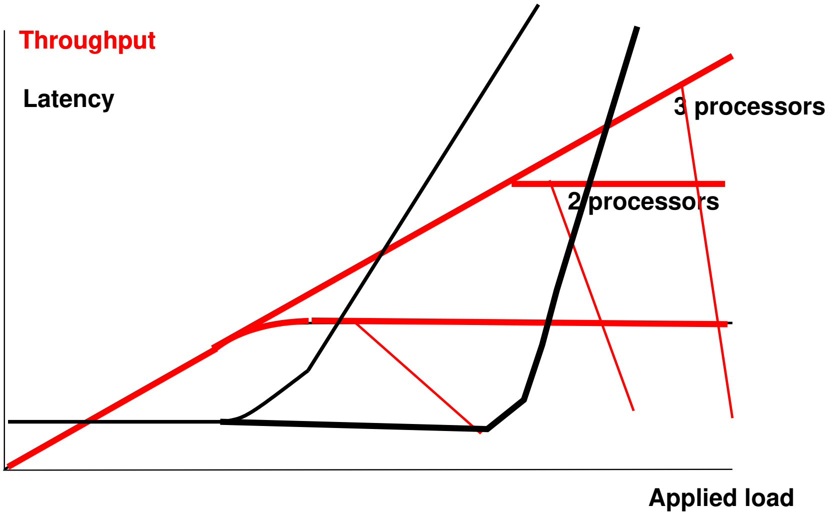


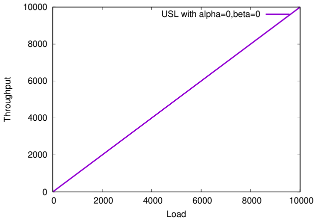
Scalability

Gunther's law

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

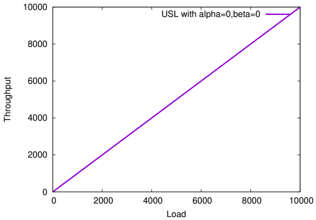
where:
N is demand
α is the amount of serialisation: represents Amdahl's law
β is the coherency delay in the system.
C is Capacity or Throughput

Scalability



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

Scalability



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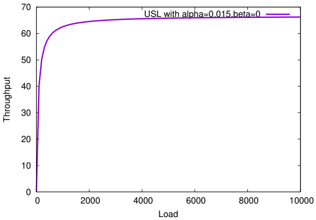

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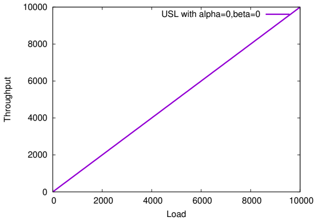

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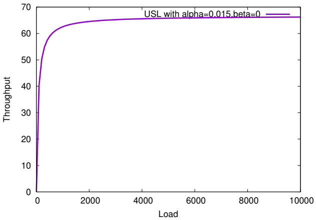

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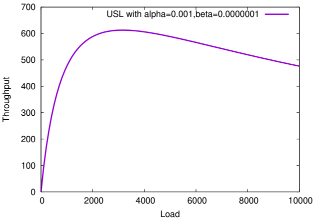

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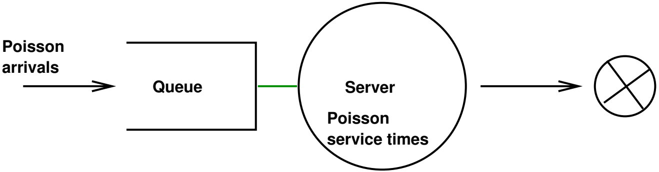
Scalability

Queueing Models



Scalability

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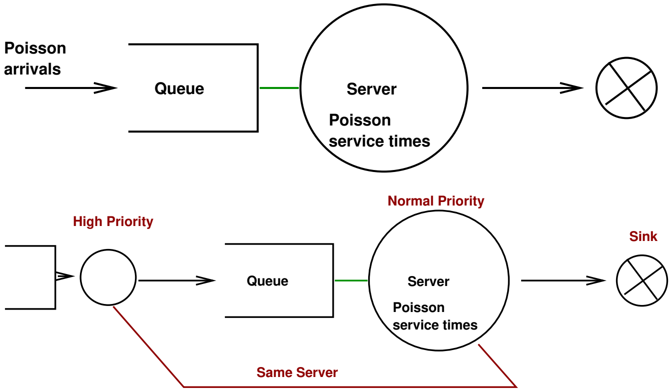
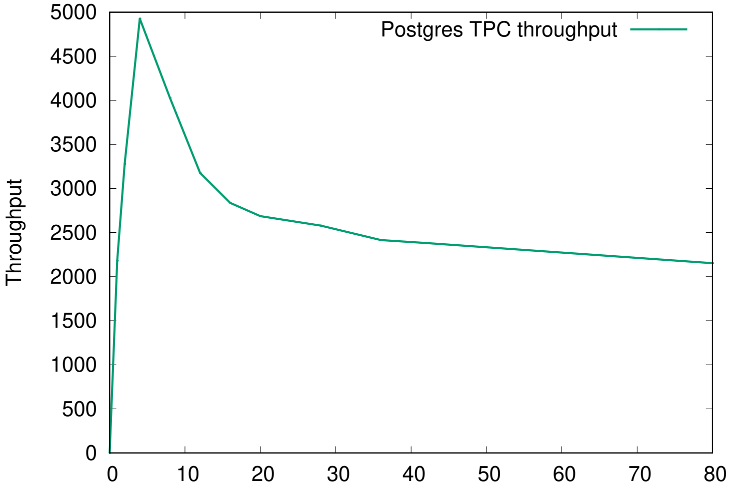


Scalability

Real examples



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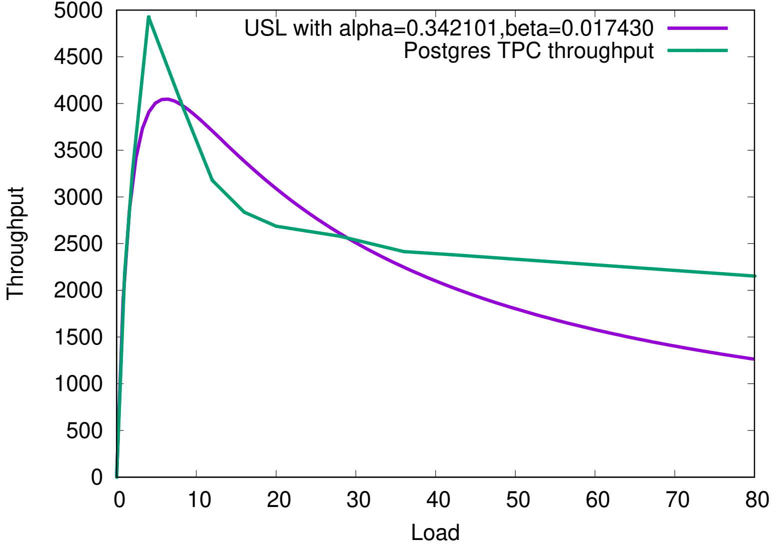

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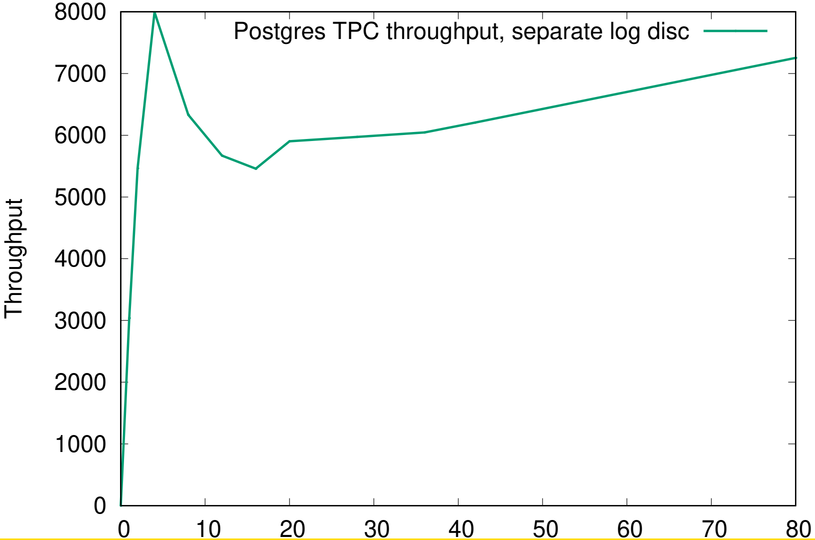
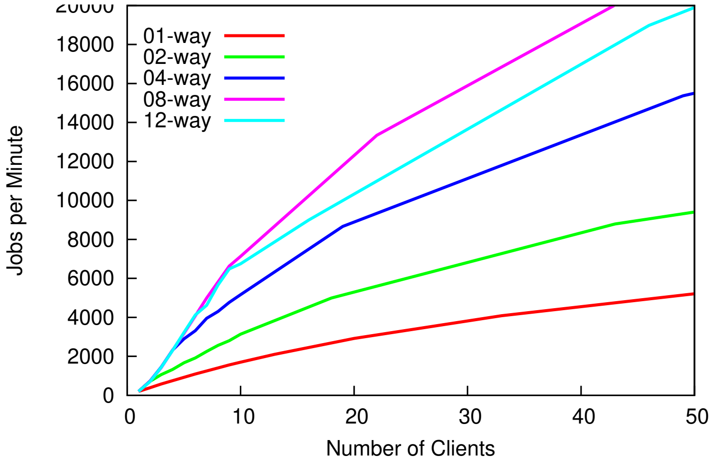


Scalability

Another example

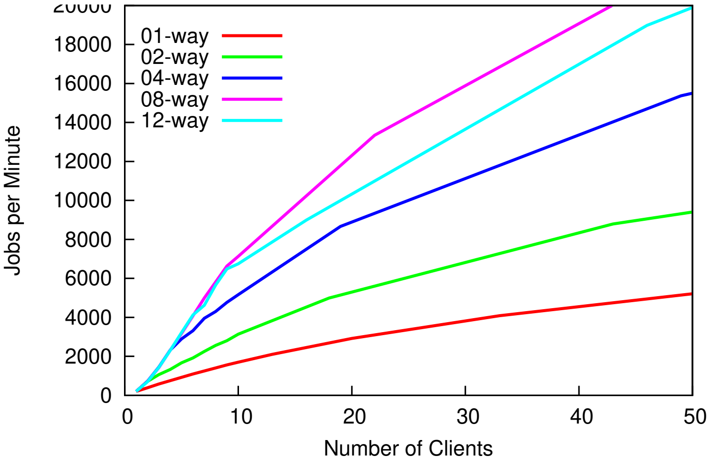
reAIM-7 on HP 16-way Itanium:



Scalability

Another example

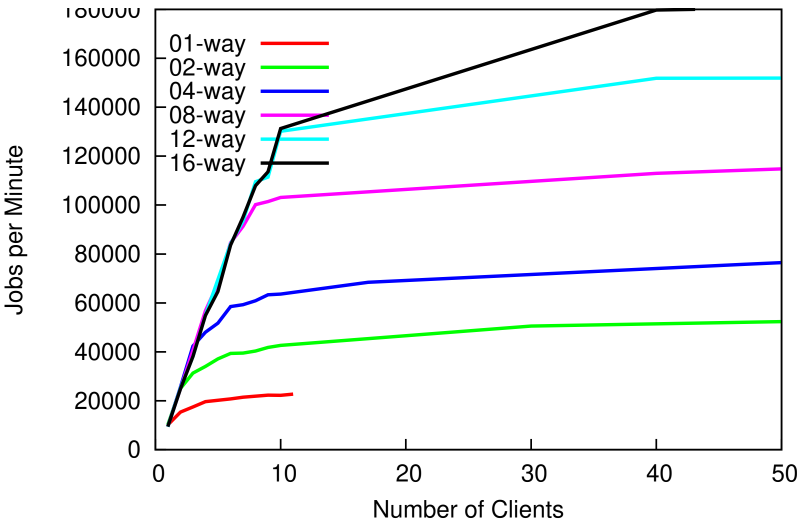
reAIM-7 on HP 16-way Itanium: α huge; 12-way curve below 8 way.

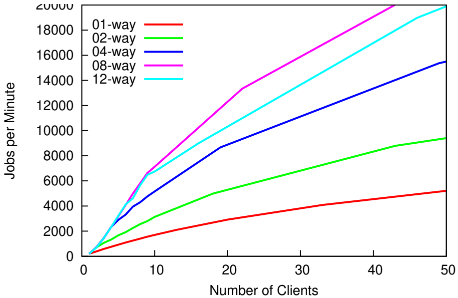


```
SPINLOCKS    HOLD            WAIT
UTIL   CON   MEAN( MAX )     MEAN( MAX )(% CPU) TOTAL      NOWAIT SPIN  RJECT NAME
72.3% 13.1% 0.5us(9.5us)  29us( 20ms)(42.5%) 50542055 86.9%  13.1% 0%    find_lock_page+0x30
0.01% 85.3% 1.7us(6.2us)  46us(4016us)(0.01%)1113     14.7%  85.3% 0%    find_lock_page+0x130
```

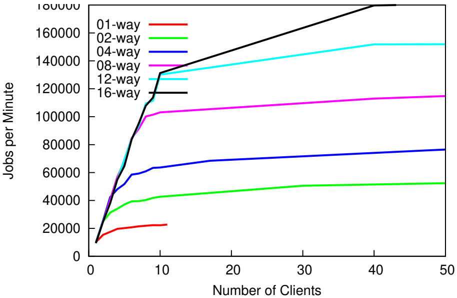
SPINLOCKS		HOLD	WAIT						
UTIL	CON	MEAN(MAX)	MEAN(MAX)	(% CPU)	TOTAL	NOWAIT	SPIN	RJECT	NAME
72.3%	13.1%	0.5us(9.5us)	29us(20ms)	(42.5%)	50542055	86.9%	13.1%	0%	find_lock_page+0x30
0.01%	85.3%	1.7us(6.2us)	46us(4016us)	(0.01%)	1113	14.7%	85.3%	0%	find_lock_page+0x130

```
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);
                               ...
```


180000
160000
140000
120000
100000
80000
60000
40000
20000
0
Jobs per Minute
0
10
20
30
40
50
Number of Clients
01-way
02-way
04-way
08-way
12-way
16-way



Spin lock



RWlock

Note Scales!

Tackling scalability problems

- Find the bottleneck

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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

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

— 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*

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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)

— Readers don’t lock
— Writers serialised.

Reader:

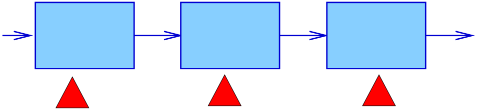
```
volatile seq;
do {
  do {
    lastseq = seq;
  } while (lastseq & 1);
  rmb();
  reader body ....
} while (lastseq != seq);
```

Writer:

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

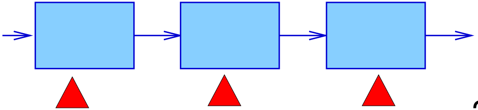
RCU

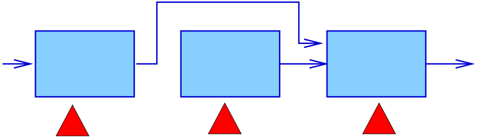
McKenney (2004), McKenney et al. (2002)

1. 

RCU

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

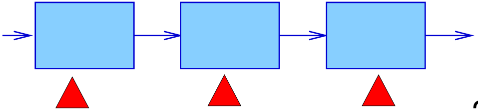
1. 

2. 

RCU

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

1.



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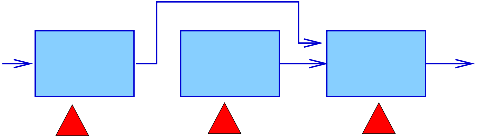

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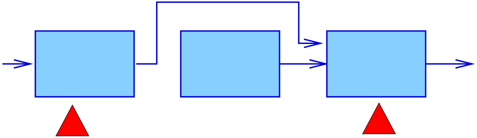
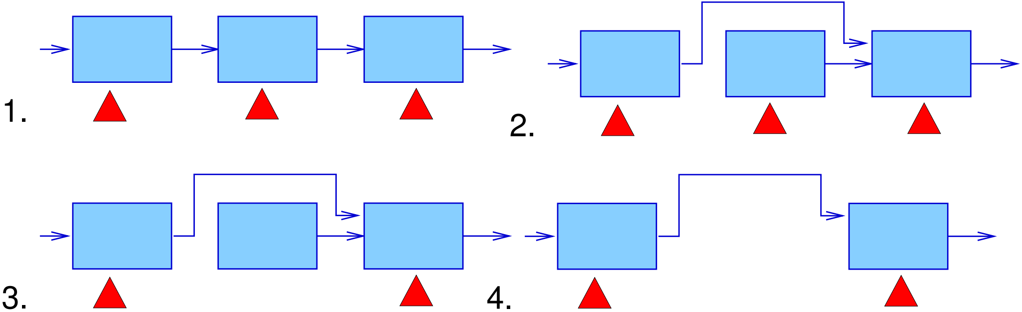


RCU

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



Background Reading I

McKenney, P. E. (2004), Exploiting Deferred Destruction: An Analysis of Read-Copy-Update Techniques in Operating System Kernels, PhD thesis, OGI School of Science and Engineering at Oregon Health and Sciences University.
URL: *http://www.rdrop.com/users/paulmck/RCU/RCUdissertation.2004.07.14e1.pdf*

McKenney, P. E., Sarma, D., Arcangelli, A., Kleen, A., Krieger, O. & Russell, R. (2002), Read copy update, *in* 'Ottawa Linux Symp.'.
URL: *http://www.rdrop.com/users/paulmck/rclock/rcu.2002.07.08.pdf*