Virtual Memory II

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Learning Outcomes

- An understanding of TLB refill:
  - in general,
  - and as implemented on the R3000
- An understanding of demand-paged virtual memory in depth, including:
  - Locality and working sets
  - Page replacement algorithms
  - Thrashing

TLB Recap

- Fast associative cache of page table entries

  – Contains a subset of the page table

  – What happens if required entry for translation is not present (a *TLB miss*)?

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TLB Recap

- TLB may or may not be under OS control
  - Hardware-loaded TLB
    - On miss, hardware performs PT lookup and reloads TLB
    - Example: Pentium
  - Software-loaded TLB
    - On miss, hardware generates a TLB miss exception, and exception handler reloads TLB
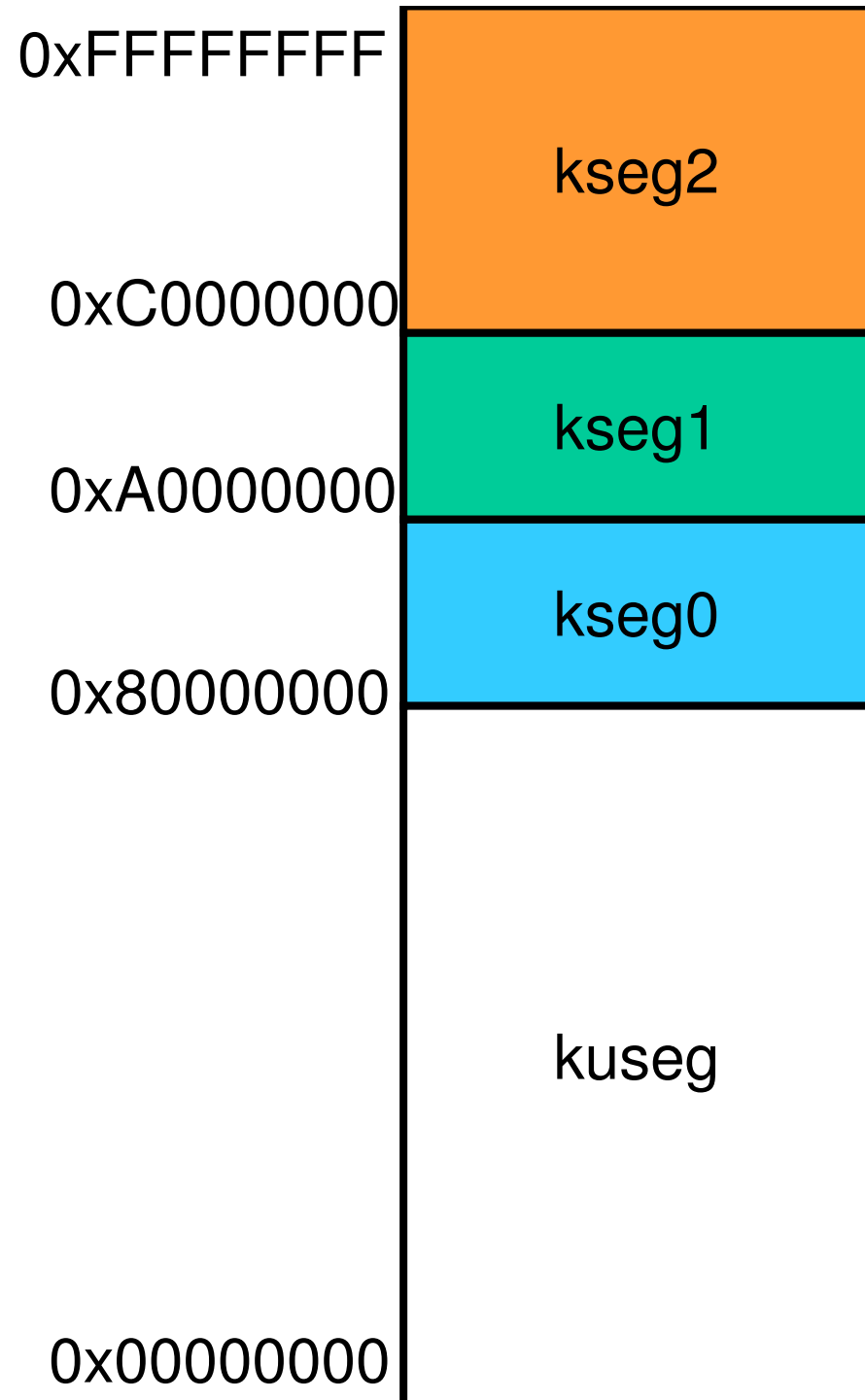   - Example: MIPS

Aside: even if filled by software

- TLB still a hardware-based translator

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R3000 TLB Handling

- TLB refill is handled by software
  - An exception handler
- TLB refill exceptions accessing kuseg are expected to be frequent
  - CPU optimised for handling kuseg TLB refills by having a special exception handler just for TLB refills

0xFFFFFFFF	kseg2
0xC0000000	kseg1
0xA0000000	kseg0
0x80000000	kuseg
0x00000000	

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Exception Vectors

Program address	"segment"	Physical Address	Description
0x8000 0000	kseg0	0x0000 0000	TLB miss on *kuseg* reference only.
0x8000 0080	kseg0	0x0000 0080	All other exceptions.
0xbfc0 0100	kseg1	0x1fc0 0100	Uncached alternative *kuseg* TLB miss entry point (used if *SR* bit BEV set).
0xbfc0 0180	kseg1		alternative for all other s, used if *SR* bit BEV set).
0xbfc0 0000	kseg1		exception".

Special exception vector for kuseg TLB refills

Table 4.1. Reset and ex ... ors) for R30xx family

Special Exception Vector

- Can be optimised for TLB refill only
  - Does not need to check the exception type
  - Does not need to save any registers
    - It uses a specialised assembly routine that only uses k0 and k1.
  - Does not check if PTE exists
    - Assumes virtual linear array – see extended OS notes

- With careful data structure choice, exception handler can be made very fast

- An example routine

```
mfc0 k1,C0_CONTEXT
mfc0 k0,C0_EPC # mfc0 delay
                #  slot
lw k1,0(k1) # may double
   # fault (k0 = orig EPC)
nop
mtc0 k1,C0_ENTRYLO
nop
tlbwr
jr k0
rfe
```

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MIPS VM Related Exceptions

- TLB refill
  - Handled via special exception vector
  - Needs to be very fast
- Others handled by the general exception vector
  - TLB Mod
    - TLB modify exception, attempt to write to a read-only page
  - TLB Load
    - Attempt it load from a page with an invalid translation
  - TLB Store
    - Attempt to store to a page with an invalid translation
  - Note: these can be slower as they are mostly either caused by an error, or non-resident page.
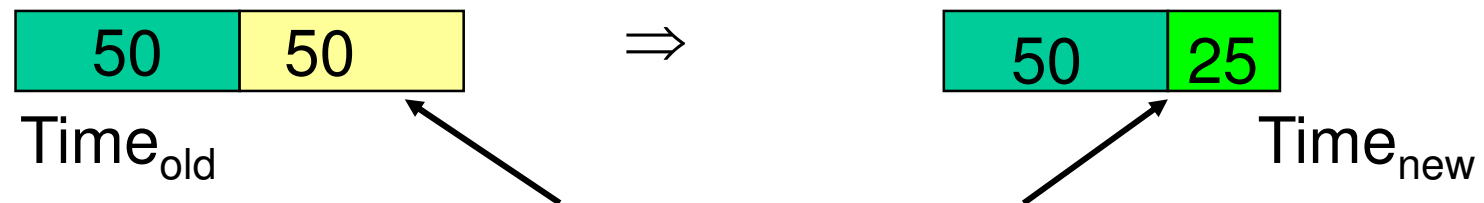   - We never optimise for errors, and page-loads from disk dominate the fault resolution cost.

<Intermezzo>

Amdahl's law

- States that overall performance improvement is limited by the fraction of time an enhancement can be used

Law of diminishing returns

50	50

Time_{old}

$\Rightarrow$

50	25

Time_{new}

fraction in enhanced mode = 0.5 (based on old system)
Speedup of enhanced mode = 2

Amdahl's law

- States that overall performance improvement is limited by the fraction of time an enhancement can be used

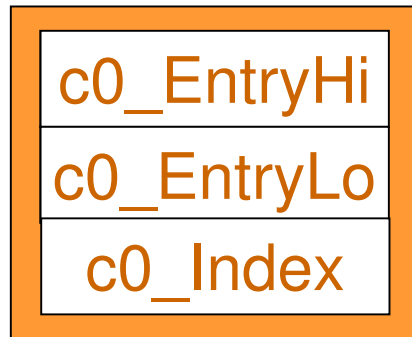$$Speed \dots Enhanced \dots$$

Make the common case fast!

</Intermezzo>

c0 Registers

- c0_EPC
  - The address of where to restart after the exception
- c0_status
  - Kernel/User Mode bits, Interrupt control
- c0_cause
  - What caused the exception
- c0_badvaddr
  - The address of the fault
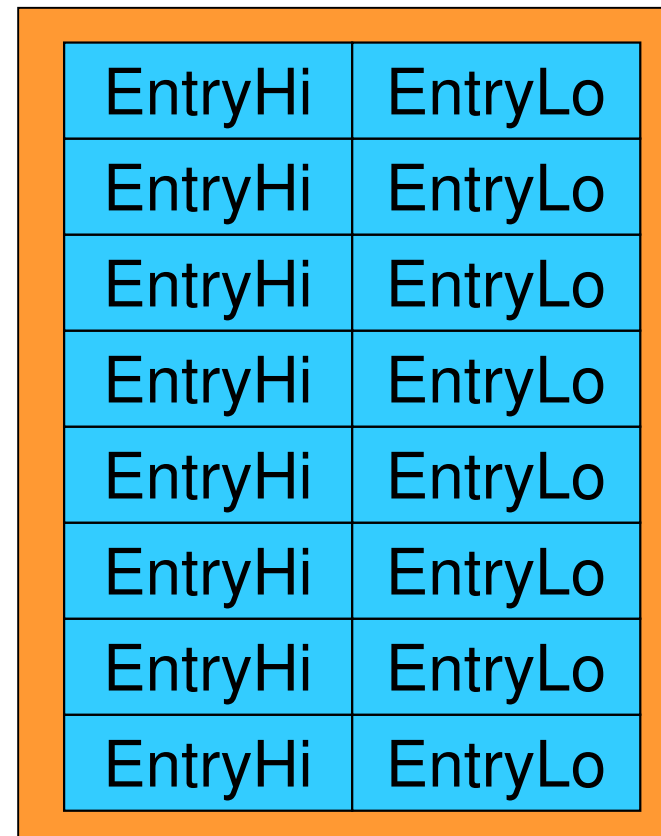
The TLB and EntryHi,EntryLo

c0 Registers

c0_EntryHi
c0_EntryLo
c0_Index

Used to read and write individual TLB entries

TLB

EntryHi	EntryLo
EntryHi	EntryLo
EntryHi	EntryLo
EntryHi	EntryLo
EntryHi	EntryLo
EntryHi	EntryLo
EntryHi	EntryLo
EntryHi	EntryLo

Each TLB entry contains

• EntryHi to match page# and ASID

• EntryLo which contains frame# and protection

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c0 Registers

31	12	11	6	5	0
VPN		ASID		0	

EntryHi Register (TLB key fields)

31	12	11	10	9	8	7	0
PFN		N	D	V	G	0	

EntryLo Register (TLB data fields)

- N = Not cacheable
- D = Dirty = Write protect
- G = Global (ignore ASID in lookup)

- V = valid bit
- 64 TLB entries
- Accessed via software through Cooprocessor 0 registers
  - EntryHi and EntryLo

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c0 Index Register

- Used as an index to TLB entries
  - Single TLB entries are manipulated/viewed through EntryHi and EntryLo0
  - Index register specifies which TLB entry to change/view

Special TLB management Instructions

- *TLBR*
  - TLB read
    - EntryHi and EntryLo are loaded from the entry pointer to by the index register.
- *TLBP*
  - TLB probe
  - Set EntryHi to the entry you wish to match, index register is loaded with the index to the matching entry
- *TLBWR*
  - Write EntryHi and EntryLo to a psuedo-random location in the TLB
- *TLBWI*
  - Write EntryHi and EntryLo to the location in the TLB pointed to by the Index register.

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Cooprocessor 0 registers on a refill exception

c0.EPC ← PC

c0.cause.ExcCode ← TLBL ; if read fault

c0.cause.ExcCode ← TLBS ; if write fault

c0.BadVaddr ← faulting address

c0.EntryHi.VPN ← faulting address

c0.status ← kernel mode, interrupts disabled.

c0.PC ← 0x8000 0000

Outline of TLB miss handling

- ## Software does:
  - Look up PTE corresponding to the faulting address
  - If found:
    - load c0_EntryLo with translation
    - load TLB using TLBWR instructions
    - return from exception
  - Else, page fault

- ## The TLB entry (i.e. c0_EntryLo) can be:
  - (theoretically) created on the fly, or
  - stored completely in the right format in page table
    - more efficient

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OS/161 Refill Handler

- After switch to kernel stack, it simply calls the common exception handler
    - Stacks all registers
    - Can (and does) call 'C' code
    - Unoptimised
    - Goal is ease of kernel programming, not efficiency

- Does not have a page table
    - It uses the 64 TLB entries and then panics when it runs out.
        - Only support 256K user-level address space

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Demand Paging/Segmentation

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Demand Paging/Segmentation

- With VM, only parts of the program image need to be resident in memory for execution.

- Can transfer presently unused pages/segments to disk

- Reload non-resident pages/segment *on demand*.
  - Reload is triggered by a page or segment fault
  - Faulting process is blocked and another scheduled
  - When page/segment is resident, faulting process is restarted
  - May require freeing up memory first
    - Replace current resident page/segment
    - How determine replacement "victim"?
  - If victim is unmodified ("clean") can simply discard it
    - This is reason for maintaining a "dirty" bit in the PT

- Why does demand paging/segmentation work?
  - Program executes at full speed only when accessing the resident set.
  - TLB misses introduce delays of several microseconds
  - Page/segment faults introduce delays of several milliseconds
  - Why do it?
- Answer
  - Less physical memory required per process
    - Can fit more processes in memory
   - Improved chance of finding a runnable one
  - Principle of locality

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Principle of Locality

- An important observation comes from empirical studies of the properties of programs.
  - Programs tend to reuse data and instructions they have used recently.
  - **90/10 rule**
    "A program spends 90% of its time in 10% of its code"
- We can exploit this *locality of references*
- An implication of locality is that we can reasonably predict what *instructions* and *data* a program will use in the near future based on its accesses in the recent past.

- **Two different types** of locality have been observed:

  - *Temporal* locality: states that recently accessed items are likely to be accessed in the near future.

  - *Spatial* locality: says that items whose addresses are near one another tend to be referenced close together in time.

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Locality In A Memory-Reference Pattern
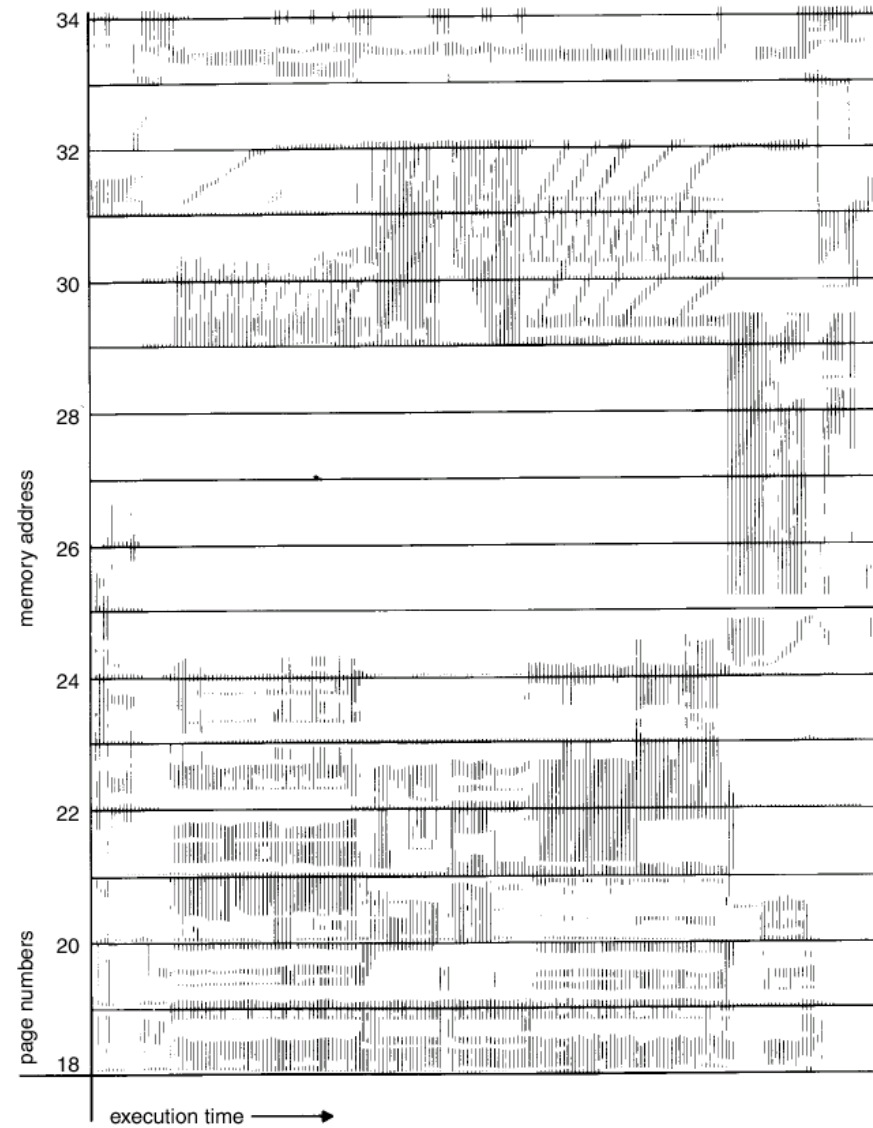
Working Set

- The pages/segments required by an application in a time window (Δ)is called its memory **working set**.

- Working set is an approximation of a programs' locality
  - if Δ too small will not encompass entire locality.
  - if Δ too large will encompass several localities.
  - if $\Delta = \infty \Rightarrow$ will encompass entire program.
  - Δ's size is an application specific tradeoff

- System should keep resident at least a process's working set
  - Process executes while it remains in its working set

- Working set tends to change gradually
  - Get only a few page/segment faults during a time window
  - Possible to make intelligent guesses about which pieces will be needed in the future
    - May be able to pre-fetch page/segments

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Working Set Example
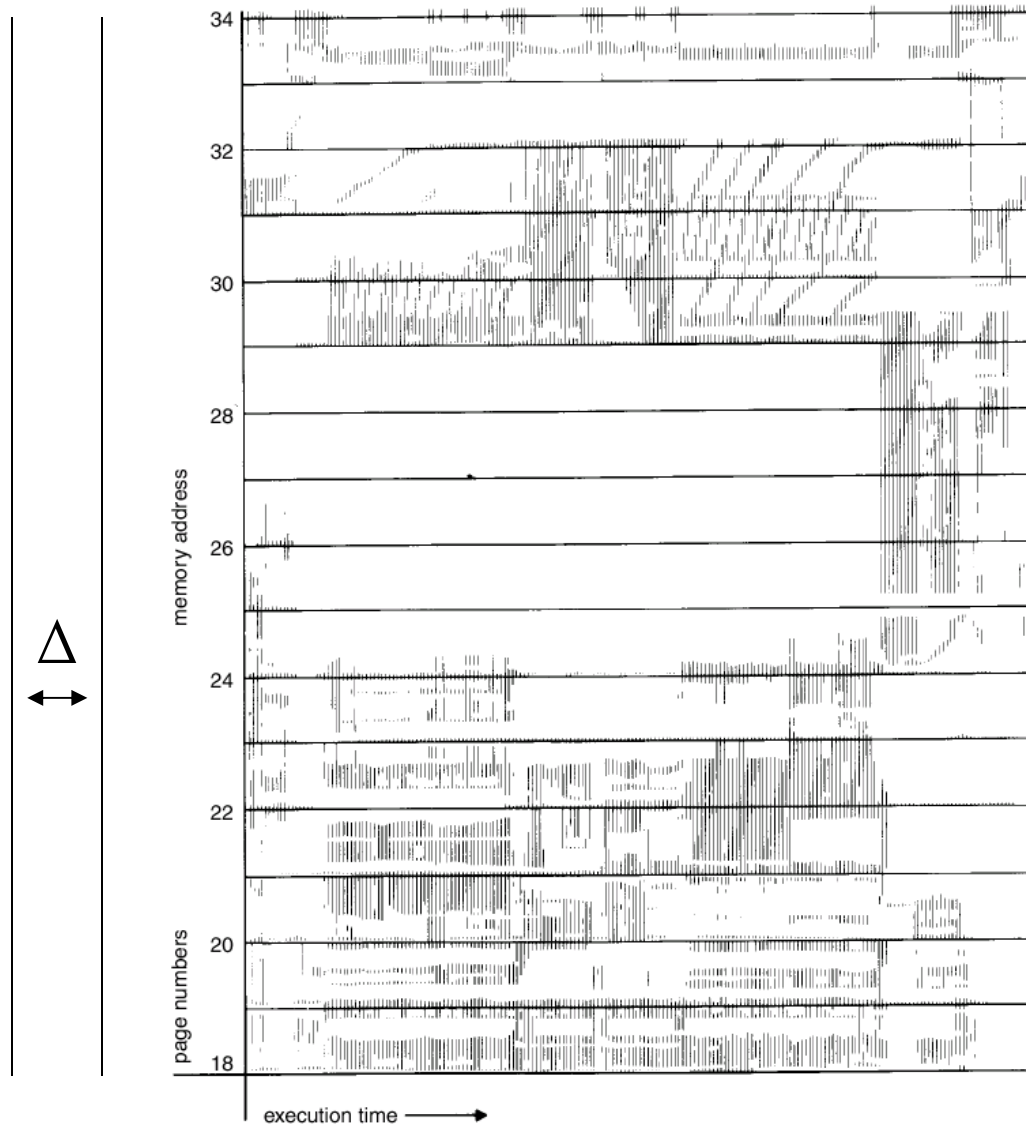
Thrashing

- CPU utilisation tends to increase with the degree of multiprogramming
  - number of processes in system
- Higher degrees of multiprogramming – less memory available per process
- Some process's working sets may no longer fit in RAM
  - Implies an increasing page fault rate
- Eventually many processes have insufficient memory
  - Can't always find a runnable process
  - Decreasing CPU utilisation
  - System become I/O limited
- This is called *thrashing*.

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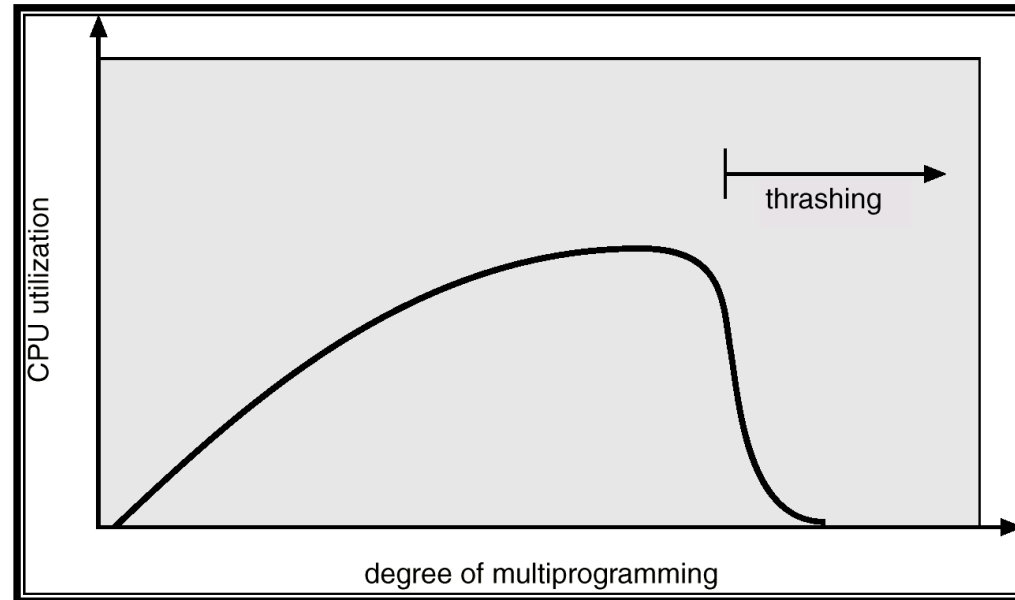
Thrashing

- **Why does thrashing occur?**

Σ working set sizes > total physical memory size

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Recovery From Thrashing

- In the presence of increasing page fault frequency and decreasing CPU utilisation
  - Suspend a few processes to reduce degree of multiprogramming
  - Resident pages of suspended processes will migrate to backing store
  - More physical memory becomes available
    - Less faults, faster progress for runnable processes
  - Resume suspended processes later when memory pressure eases

Quiz

- how does an IPT work?
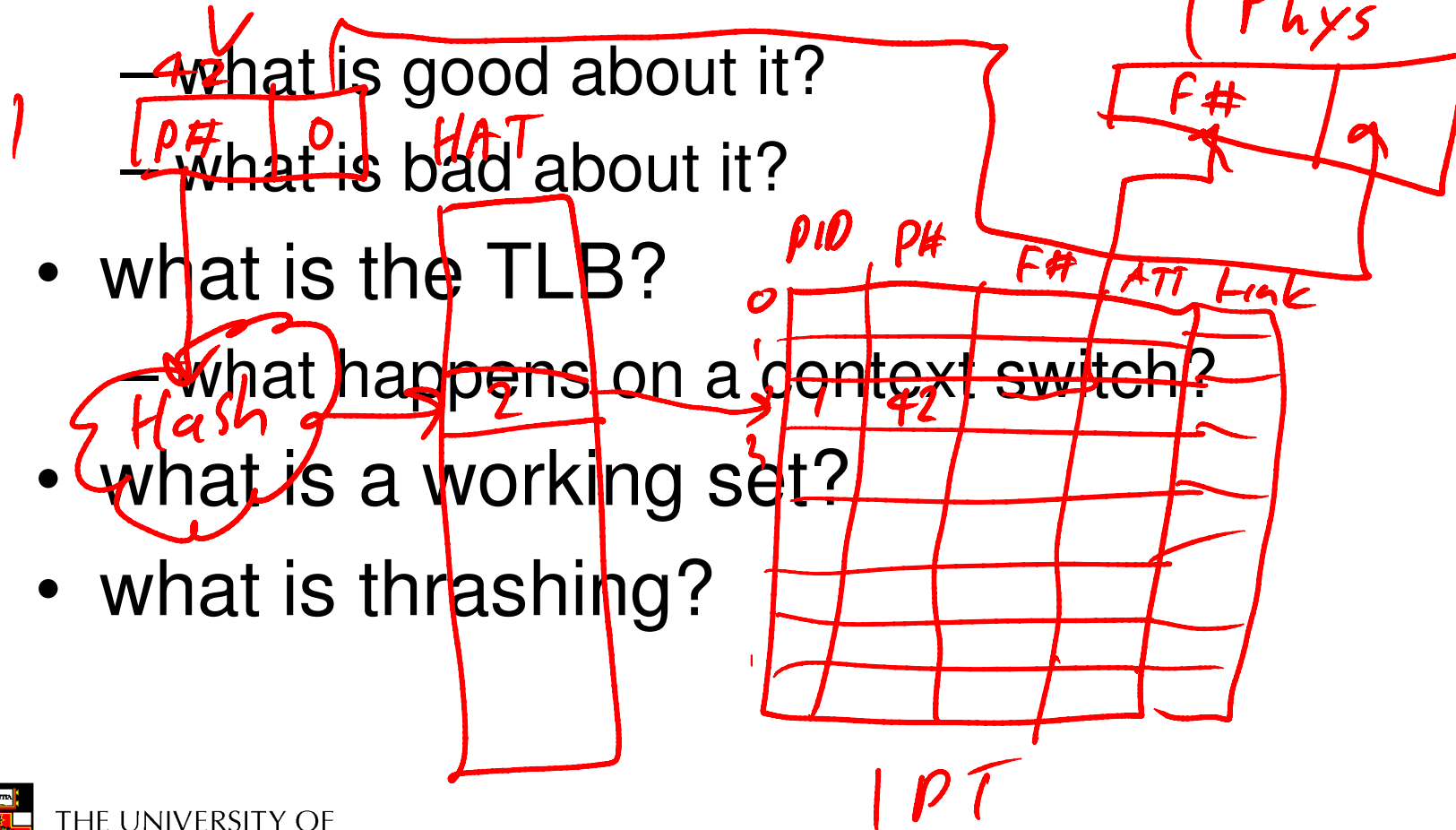 - what is good about it?
  - what is bad about it?

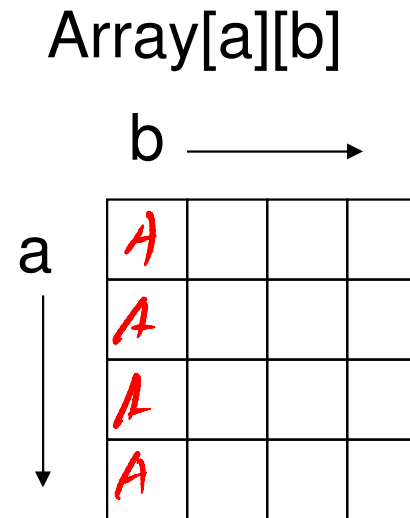- what is the TLB?
  - what happens on a context switch?

- what is a working set?

- what is thrashing?

What is the difference?

```
/* reset array */
int array[10000][10000];
int i,j;
for (i = 0; i < 10000; i++) {
   for (j = 0; j < 10000;j ++) {
      array[i][j] = 0;
      /* array[j][i] = 0 */
   }
}
```

Array[a][b]

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VM Management Policies

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VM Management Policies

- Operation and performance of VM system is dependent on a number of policies:
  - Page table format (may be dictated by hardware)
    - Multi-level
    - Hashed
  - Page size (may be dictated by hardware)
  - Fetch Policy
  - Replacement policy
  - Resident set size
    - Minimum allocation
    - Local versus global allocation
  - Page cleaning policy
  - Degree of multiprogramming

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Page Size

Increasing page size

✗ Increases internal fragmentation
  - reduces adaptability to working set size

✓ Decreases number of pages
  - Reduces size of page tables

✓ Increases TLB coverage
  - Reduces number of TLB misses

✗ Increases page fault latency
  - Need to read more from disk before restarting process

✓ Increases swapping I/O throughput
  - Small I/O are dominated by seek/rotation delays

- Optimal page size is a (work-load dependent) trade-off.

Working Set Size Generally Increases with Increasing Page Size: True/False?

1K → 4K

4 → 16K

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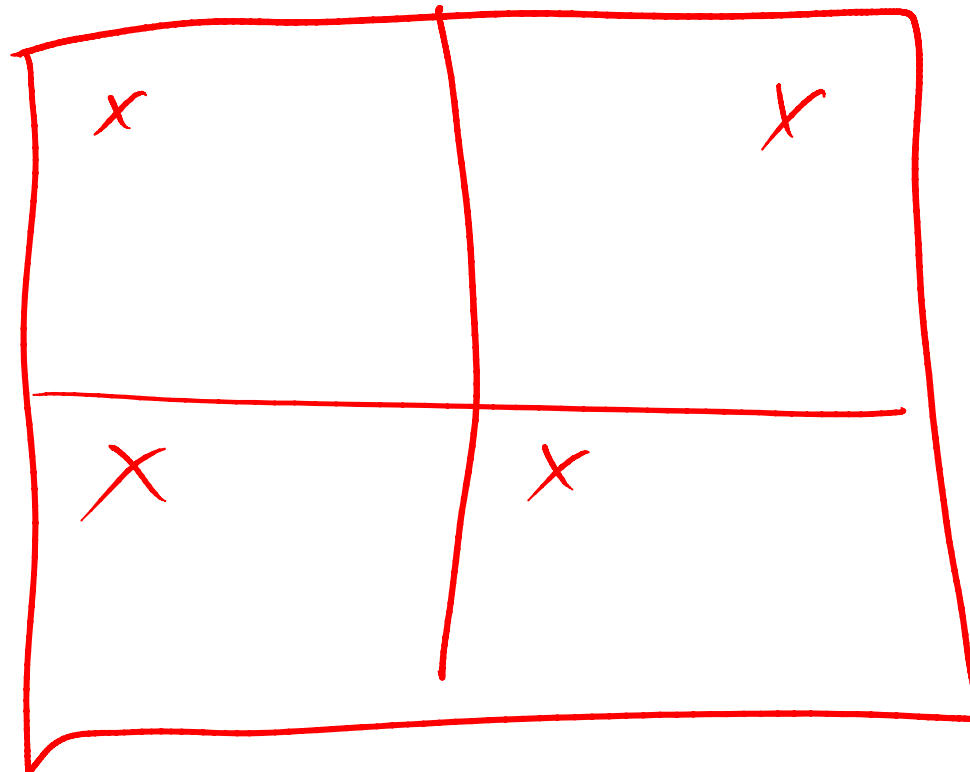
Atlas	512 words (48-bit)
Honeywell/Multics	1K words (36-bit)
IBM 370/XA	4K bytes
DEC VAX	512 bytes
IBM AS/400	512 bytes
Intel Pentium	4K and 4M bytes
ARM	4K and 64K bytes
MIPS R4000	4k – 16M bytes in powers of 4
DEC Alpha	8K - 4M bytes in powers of 8
UltraSPARC	8K – 4M bytes in powers of 8
PowerPC	4K bytes + "blocks"
Intel IA-64	4K – 256M bytes in powers of 4

Page Size

- Multiple page sizes provide flexibility to optimise the use of the TLB

- Example:

  - Large page sizes can be use for code

  - Small page size for thread stacks

- Most operating systems support only a single page size

  - Dealing with multiple page sizes is hard!

Fetch Policy

- Determines *when* a page should be brought into memory
  - *Demand paging* only loads pages in response to page faults
    - Many page faults when a process first starts
  - *Pre-paging* brings in more pages than needed at the moment
    - Improves I/O performance by reading in larger chunks
    - Pre-fetch when disk is idle
    - Wastes I/O bandwidth if pre-fetched pages aren't used
    - Especially bad if we eject pages in working set in order to pre-fetch unused pages.
    - Hard to get right in practice.

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Replacement Policy

Page fault on page 14, physical memory full, which page should we evict?

Virtual

Memory

Physical Address Space

Disk

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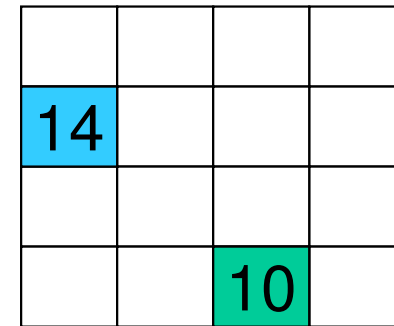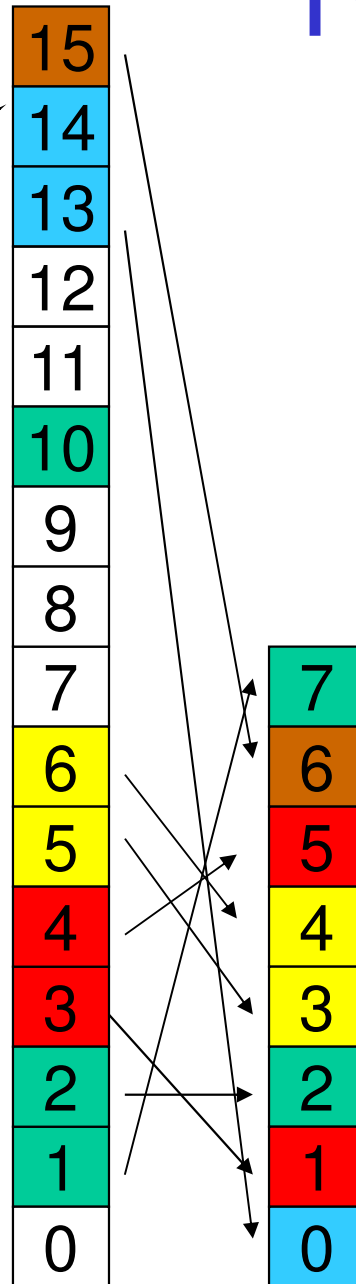
Replacement Policy

- Which page is chosen to be tossed out?
  - Page removed should be the page least likely to be references in the near future
  - Most policies attempt to predict the future behaviour on the basis of past behaviour
- Constraint: locked frames
  - Kernel code
  - Main kernel data structure
  - I/O buffers
  - Performance-critical user-pages (e.g. for DBMS)
- Frame table has a *lock* bit

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Optimal Replacement policy

- Toss the page that won't be used for the longest time
- Impossible to implement
- Only good as a theoretic reference point:
  - The closer a practical algorithm gets to *optimal*, the better
- Example:
  - Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
  - Four frames
  - How many page faults?

FIFO Replacement Policy

- First-in, first-out: Toss the oldest page
  - Easy to implement
  - Age of a page is isn't necessarily related to usage
- Example:
  - Reference string: 1,2,3,4,1,2,5,1,2,3,4,5
  - Four frames
  - How many page faults?
  - Three frames?

FIFO Replacement Policy

- First-in, first-out: Toss the oldest page
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- Example:
  - Reference string: 1,2,3,4,1,2,5,1,2,3,4,5
  - Four frames
  - How many page faults?
  - Three frames?

Belady's Anomaly

- For FIFO, more frames does not imply fewer page faults

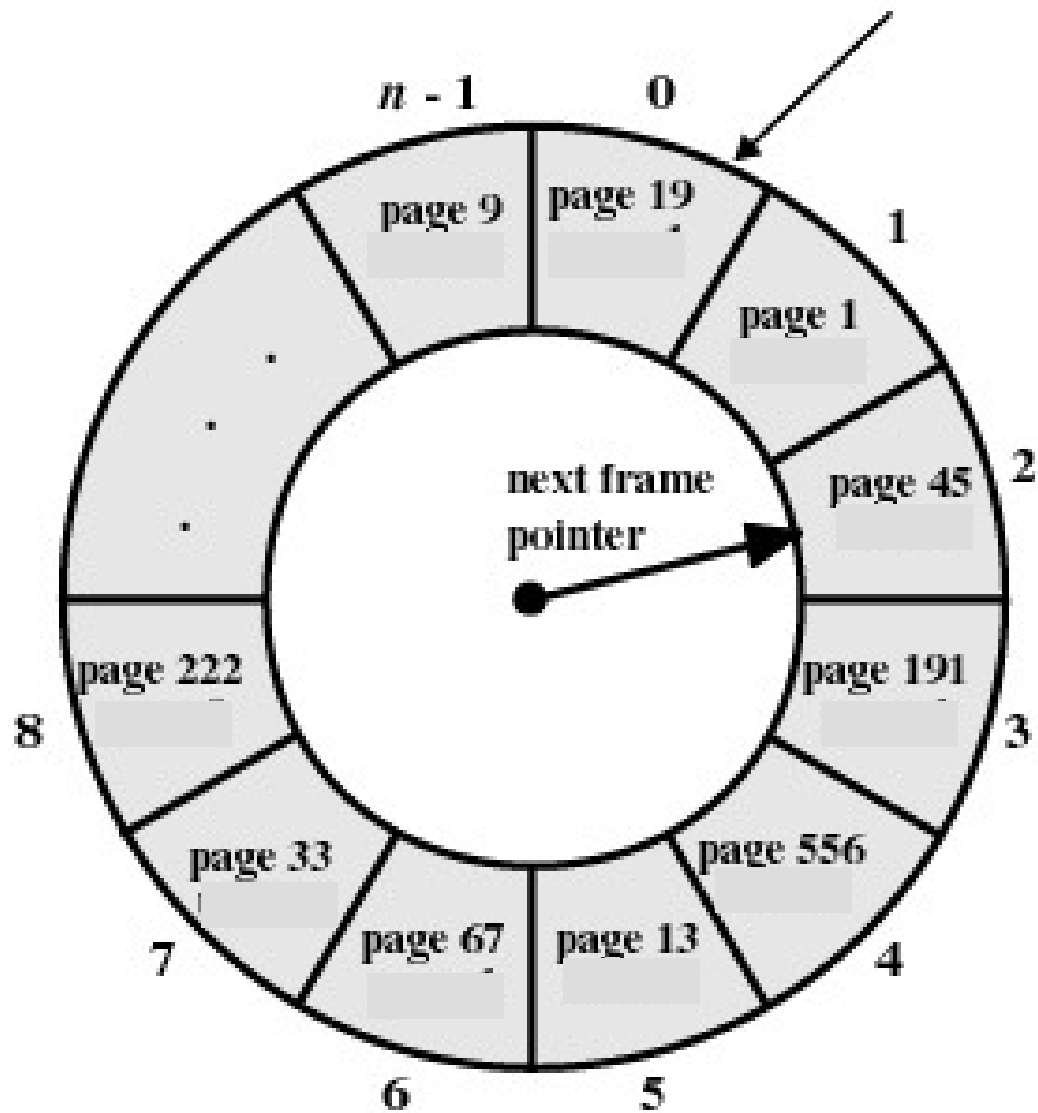# *Least Recently Used* (LRU)

- Toss the least recently used page
  - Assumes that page that has not been referenced for a long time is unlikely to be referenced in the near future
  - Will work if locality holds
  - Implementation requires a time stamp to be kept for each page, updated **on every reference**
  - Impossible to implement efficiently
  - Most practical algorithms are approximations of LRU
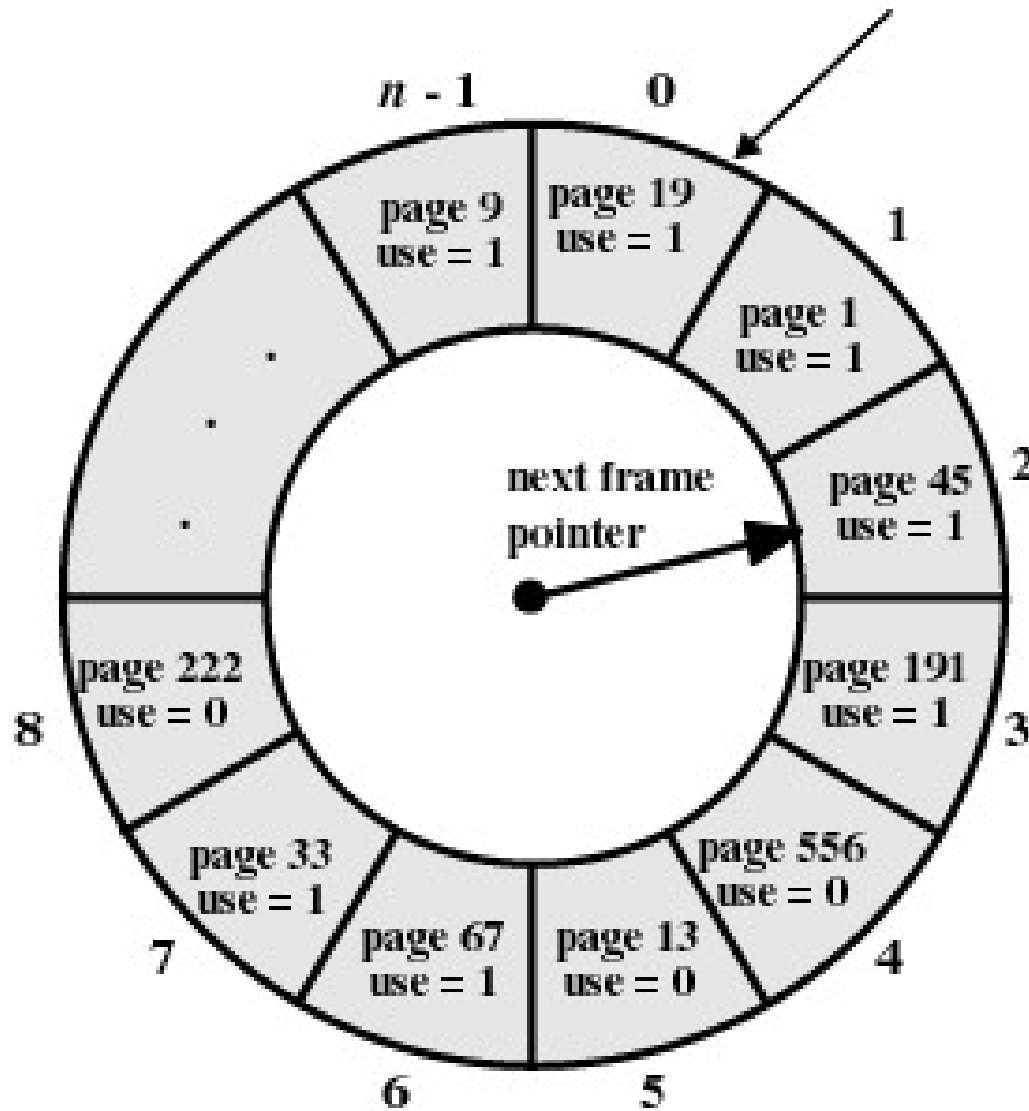
Clock Page Replacement

- Clock policy, also called *second chance*
  - Employs a *usage* or *reference* bit in the frame table.
  - Set to *one* when page is used
  - While scanning for a victim, reset all the reference bits
  - Toss the first page with a zero reference bit.

page 9 page 19

page 1

n - 1   0

1

page 45   2

next frame pointer

page 222

8

page 191

3

page 33

page 67   page 13   page 556

7   4

6   5

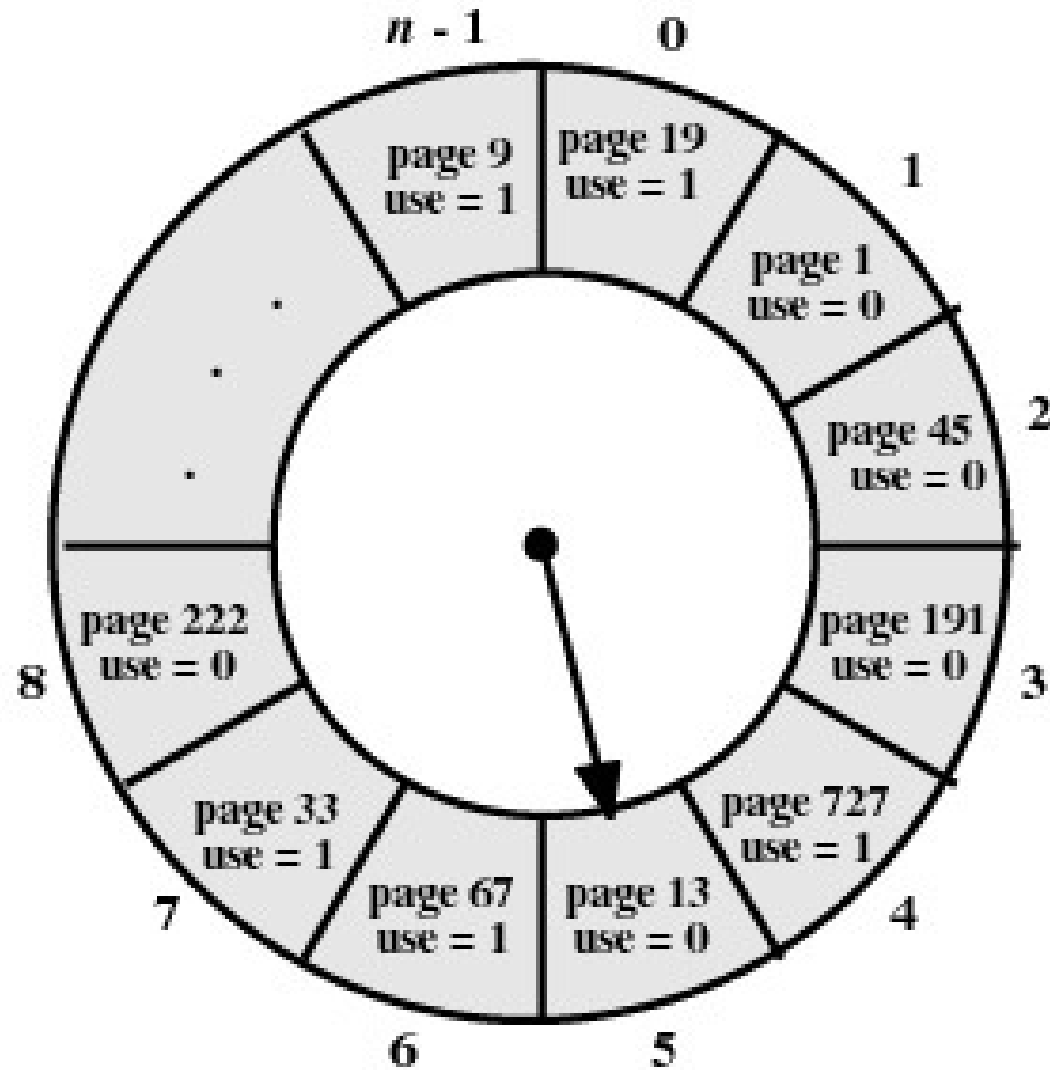(a) State of buffer just prior to a page replacement

Figure 8.16   Example of Clock Policy Operation

Assume a page fault on page 727

(a) State of buffer just prior to a page replacement

Figure 8.16 Example of Clock Policy Operation

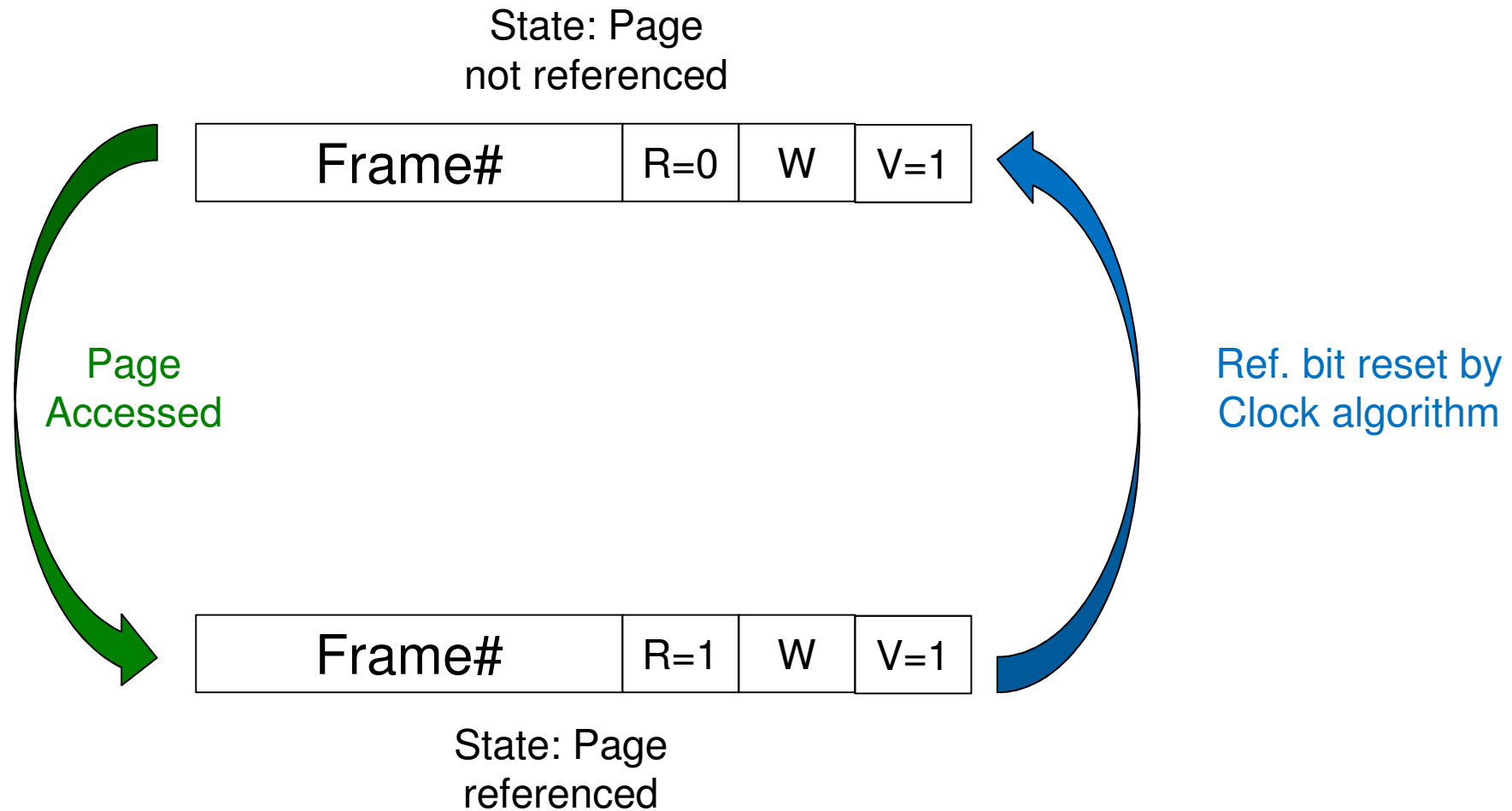(b) State of buffer just after the next page replacement

Figure 8.16   Example of Clock Policy Operation
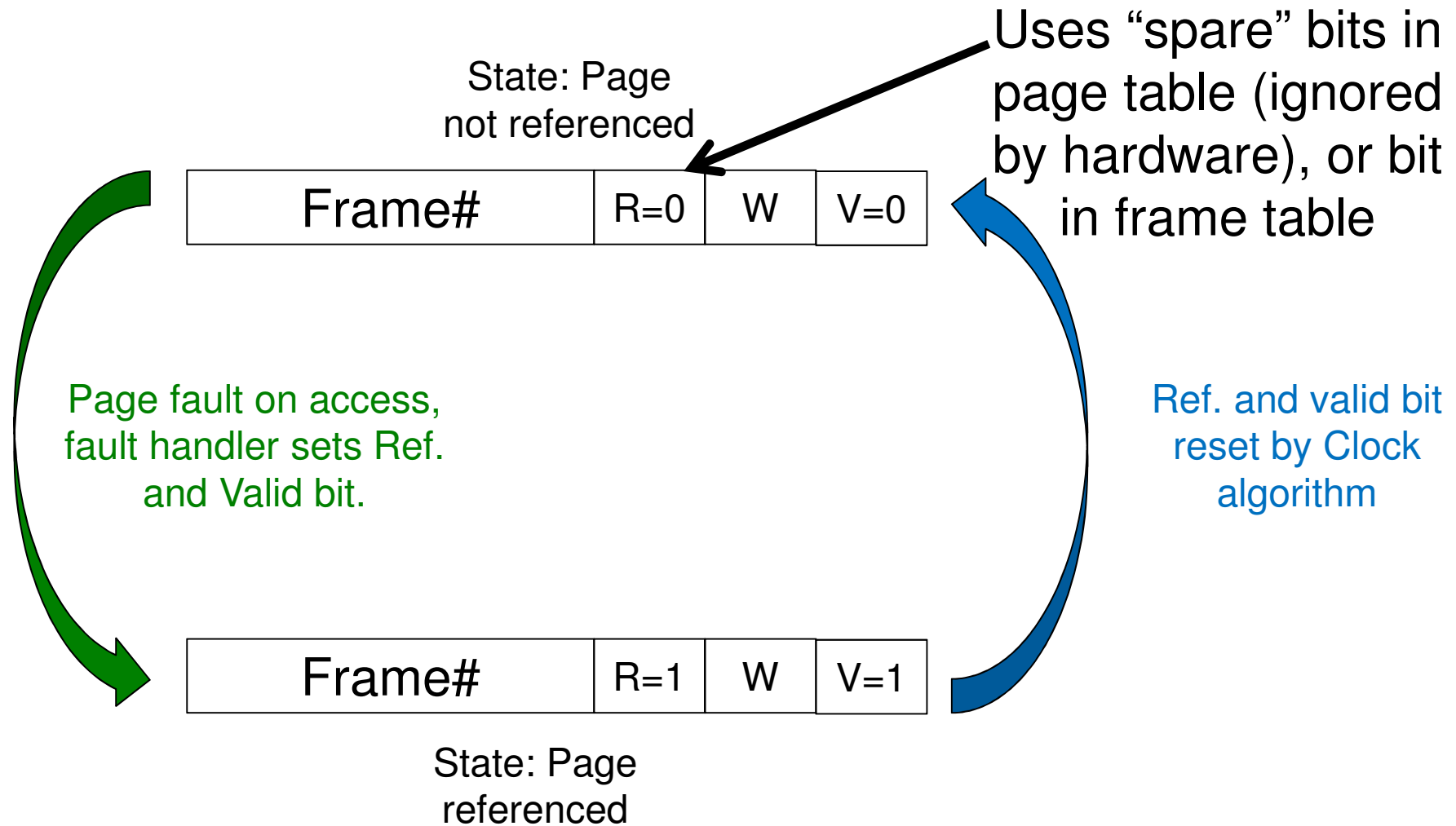
Issue

- How do we know when a page is referenced?

- Use the valid bit in the PTE:

  – When a page is mapped (valid bit set), set the reference bit

  – When resetting the reference bit, invalidate the PTE entry

  – On page fault
    - Turn on valid bit in PTE
    - Turn on reference bit

- We thus simulate a reference bit in software

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Hardware Reference Bit

State: Page
not referenced

| Frame# | R=0 | W | V=1 |

Page
Accessed

Ref. bit reset by
Clock algorithm

| Frame# | R=1 | W | V=1 |

State: Page
referenced

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Simulated Reference Bit

Uses "spare" bits in page table (ignored by hardware), or bit in frame table

State: Page not referenced

Frame#	R=0	W	V=0

Page fault on access, fault handler sets Ref. and Valid bit.

Ref. and valid bit reset by Clock algorithm

Frame#	R=1	W	V=1

State: Page referenced

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Performance

- It terms of selecting the most appropriate replacement, they rank as follows

  1. Optimal

  2. LRU

  3. Clock

  4. FIFO

- Note there are other algorithms (Working Set, WSclock, Ageing, NFU, NRU)

  - We don't expect you to know them in this course

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Resident Set Size

- ## How many frames should each process have?
    - *Fixed Allocation*
        - Gives a process a fixed number of pages within which to execute.
        - Isolates process memory usage from each other
        - When a page fault occurs, one of the pages of that process must be replaced.
        - Achieving high utilisation is an issue.
            - Some processes have high fault rate while others don't use their allocation.
    - *Variable Allocation*
        - Number of pages allocated to a process varies over the lifetime of the process

Variable Allocation, Global Scope

- – Easiest to implement
- – Adopted by many operating systems
- – Operating system keeps global list of free frames
- – Free frame is added to resident set of process when a page fault occurs
- – If no free frame, replaces one from any process

- Pro/Cons
  - – Automatic balancing across system
 - – Does not provide guarantees for important activities

Variable Allocation, Local Scope

- Allocate number of page frames to a new process based on
  - Application type
  - Program request
  - Other criteria (priority)
- When a page fault occurs, select a page from among the resident set of the process that suffers the page fault
- *Re-evaluate allocation from time to time!*

Page-Fault Frequency Scheme
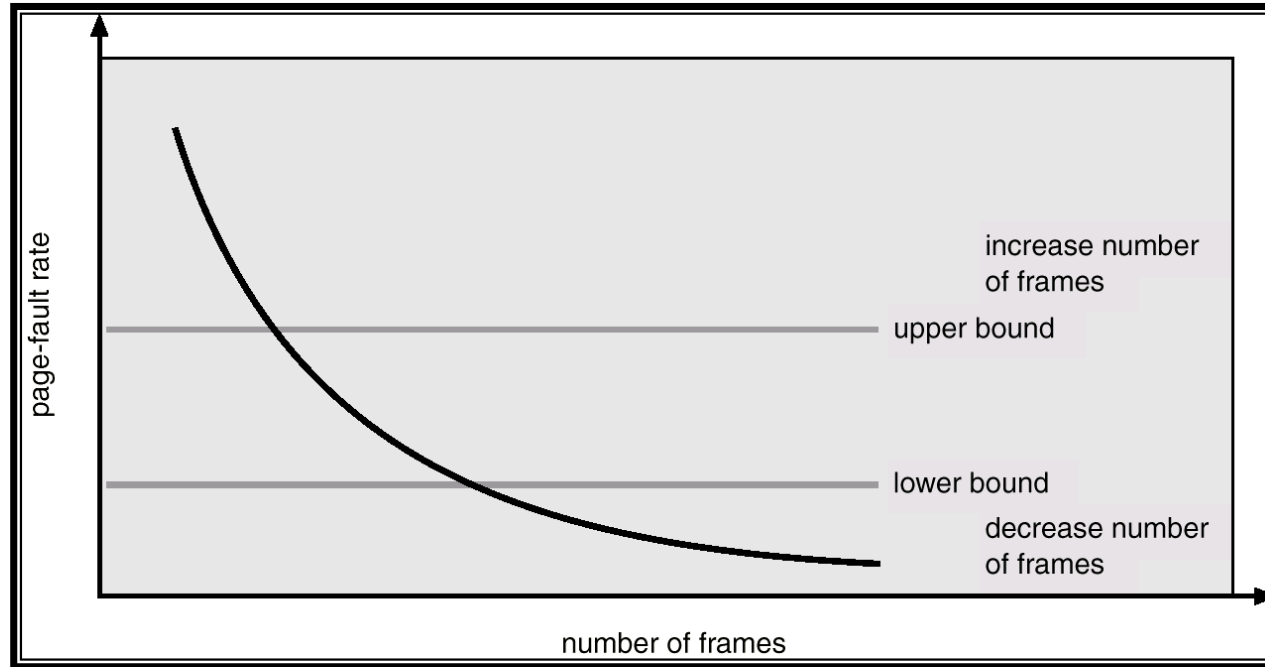
- Establish "acceptable" page-fault rate.
  - If actual rate too low, process loses frame.
  - If actual rate too high, process gains frame.

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Cleaning Policy

- ## Observation
  - Clean pages are much cheaper to replace than dirty pages
- ## Demand cleaning
  - A page is written out only when it has been selected for replacement
  - High latency between the decision to replace and availability of free frame.
- ## Precleaning
  - Pages are written out in batches (in the background, the *pagedaemon*)
  - Increases likelihood of replacing clean frames
  - Overlap I/O with current activity
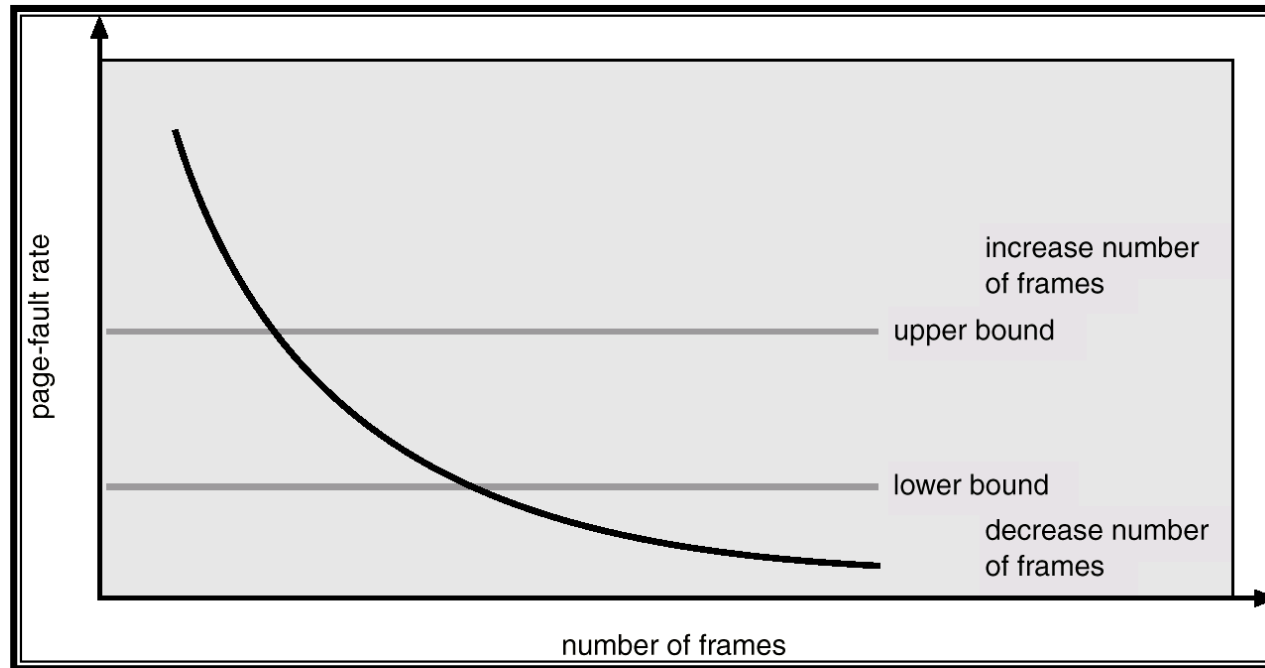
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Load Control (Degree of multiprogramming)

- Determines the number of runnable processes
- Controlled by:
  - Admission control
    - Only let new process's threads enter *ready* state if enough memory is available
  - Suspension:
    - Move all threads of some process into a special *suspended* state
    - Swap complete process image of suspended process to disk
- Trade-off
  - Too many processes will lead to thrashing
  - Too few will lead to idle CPU

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Load Control Considerations

- Can use page fault frequency.

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