

## Virtual Memory II

## 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*)?

## TLB Recap

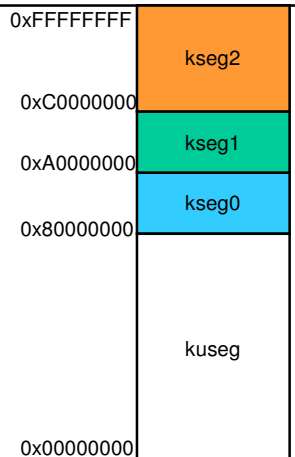
- TLB may or may not be under OS control
  - Hardware-loaded TLB
    - On miss, hardware performs PT lookup and reloads TLB
    - Example: Pentium
  - Software-loaded TLB
    - On miss, hardware generates a TLB miss exception, and exception handler reloads TLB
    - Example: MIPS

## Aside: even if filled by software

- TLB still a hardware-based translator

## 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



## Exception Vectors

Program address	"segment"	Physical Address	Description
0x8000 0000	kseg0	0x0000 0000	TLB miss on <i>kuseg</i> reference only.
0x8000 0080	kseg0	0x0000 0080	All other exceptions.
0xbf00 0100	kseg1	0x1fc0 0100	Uncached alternative <i>kuseg</i> TLB miss entry point (used if <i>SR</i> bit BEV set).
0xbf00 0180	kseg1		Alternative for all other exceptions, used if <i>SR</i> bit BEV set.
0xbf00 0000	kseg1		Special exception vector for <i>kuseg</i> TLB refills.

Special exception vector for *kuseg* TLB refills

## 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
    
```

## 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 to 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



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

## Amdahl's law



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**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

## 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 Coprocessor 0 registers
  - EntryHi and EntryLo

## 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 pseudo-random location in the TLB
- **TLBWI**
  - Write EntryHi and EntryLo to the location in the TLB pointed to by the Index register.

## Coprocessor 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:
  - created on the fly, or
  - stored completely in the right format in page table
    - more efficient

## 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

## Demand Paging/Segmentation

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- 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

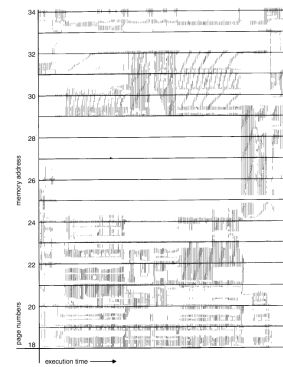
- Why does demand paging/segmentation work?
  - Program executes at full speed only when accessing the resident set.
  - TLB misses introduce delays of several microseconds
  - Page/segment faults introduce delays of several milliseconds
  - Why do it?
- Answer
  - Less physical memory required per process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

## 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.

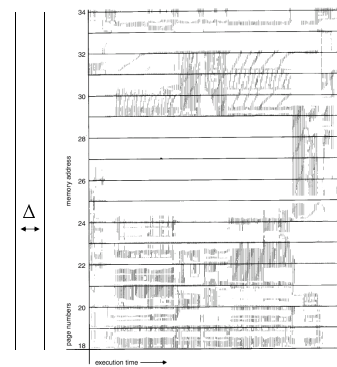
## Locality In A Memory-Reference Pattern



## Working Set

- The pages/segments required by an application in a time window ( $\Delta$ ) is called its memory **working set**.
- Working set is an approximation of a program's locality
  - if  $\Delta$  too small will not encompass entire locality.
  - if  $\Delta$  too large will encompass several localities.
  - if  $\Delta = \infty \Rightarrow$  will encompass entire program.
  - $\Delta$ '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

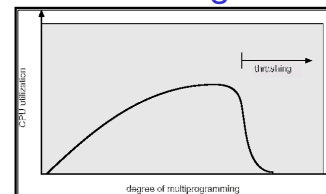
## Working Set Model



## 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**.

## Thrashing



- Why does thrashing occur?  
 $\Sigma$  working set sizes > total physical memory size

## 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

0 | 0011 → 11  
0 | 1011 → 01

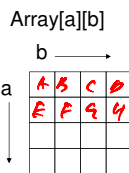
2 bit - p<sup>4</sup> size  
4 bit natural

- 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 */
    }
}
    
```



A|B|C|D|E|F|G|H|...--

## VM Management Policies

## 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

## 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?

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

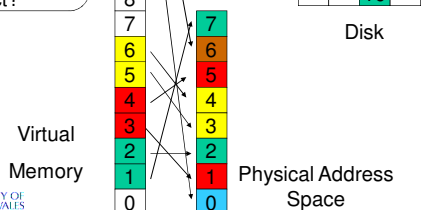
- Multiple page sizes provide flexibility to optimise the use of the TLB
- Example:
  - Large page sizes can be use for code
  - Small page size for thread stacks
- Most operating systems support only a single page size
  - Dealing with multiple page sizes is hard!

## 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.

## Replacement Policy

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



## 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

## 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?

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## Belady's Anomaly

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

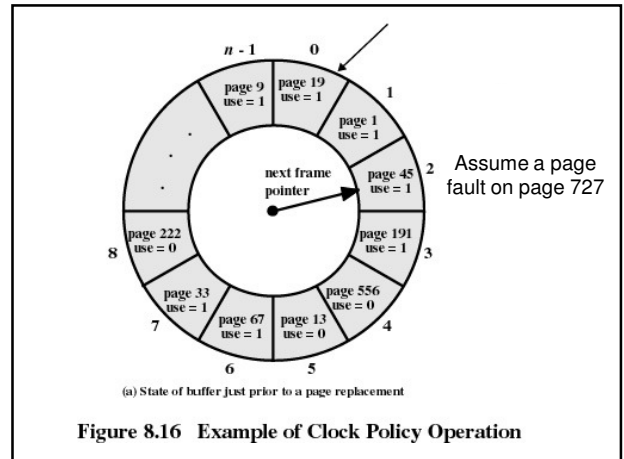
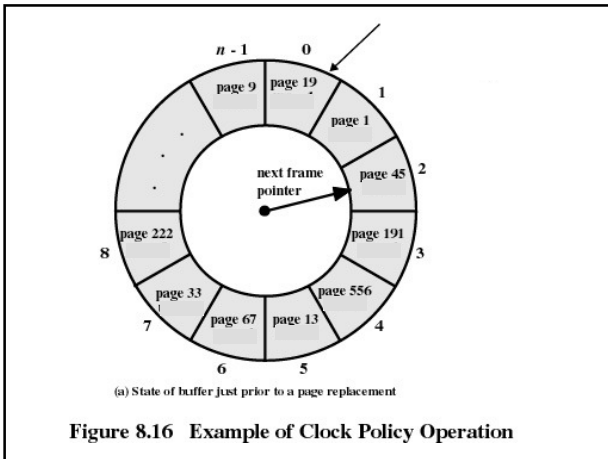
## Least Recently Used (LRU)

- 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

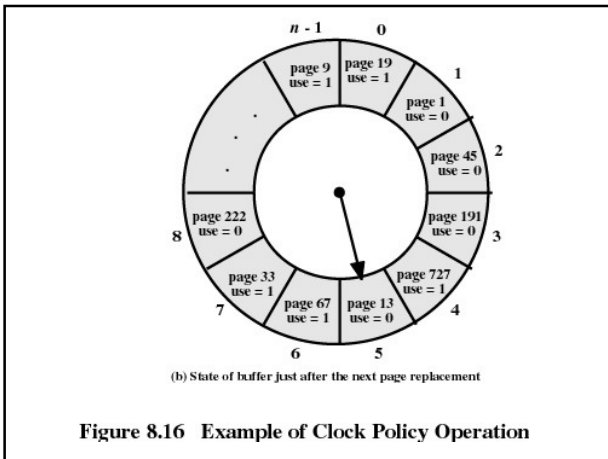
## Clock Page Replacement

- 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.





Assume a page fault on page 727



## 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

## Simulating a Reference Bit

## 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

## Resident Set Size

- How many frames should each process have?
  - *Fixed Allocation*
    - Gives a process a fixed number of pages within which to execute.
    - 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

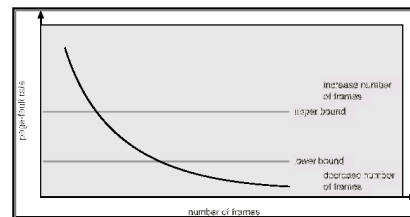
## Variable Allocation, Global Scope

- 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.

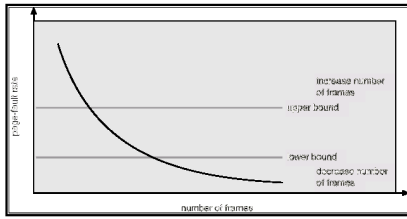
## Cleaning Policy

- **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

## 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

## Load Control Considerations



- Can use page fault frequency.