Virtual Memory & Caching

(Chapter 12-17)

CS 4410
Operating Systems

Cornell CIS
COMPUTING AND INFORMATION SCIENCE

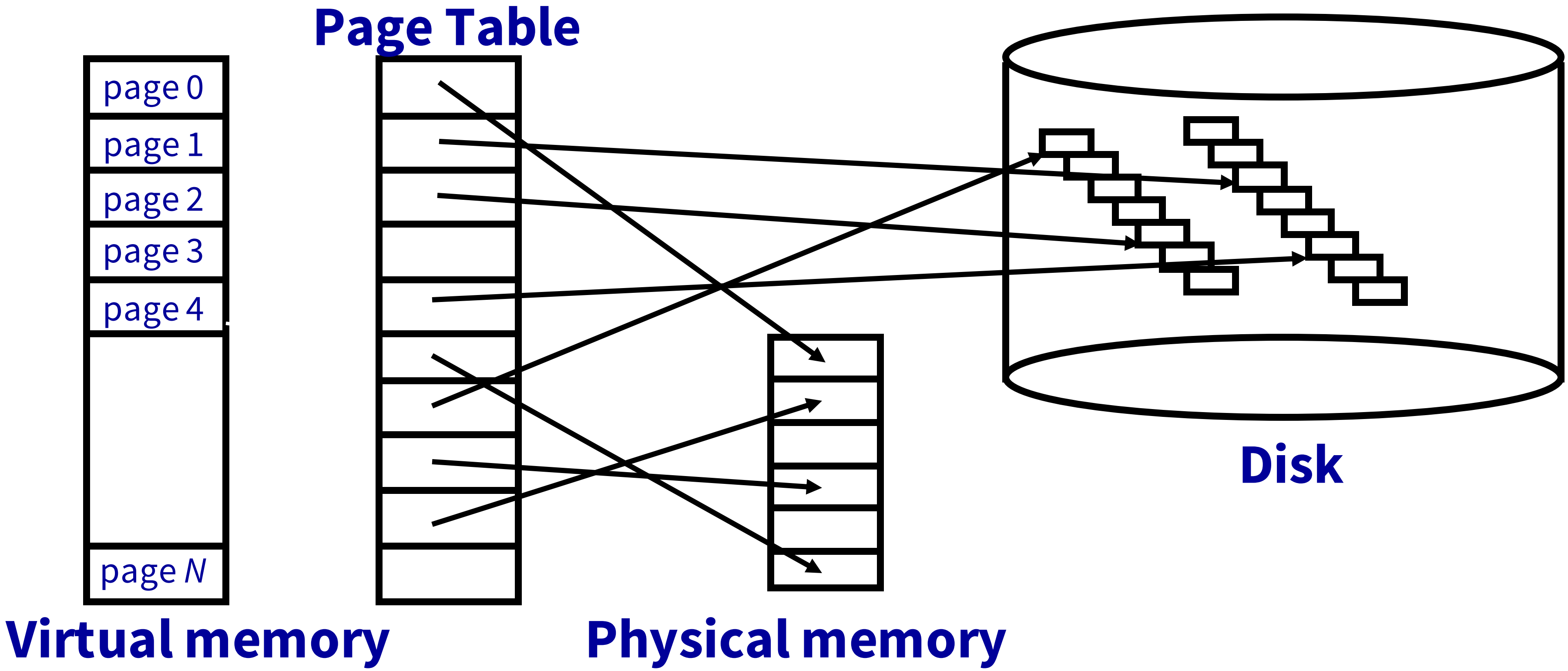
Last Time: Address Translation

- Paged Translation
- Efficient Address Translation
  - Multi-Level Page Tables
  - TLBs

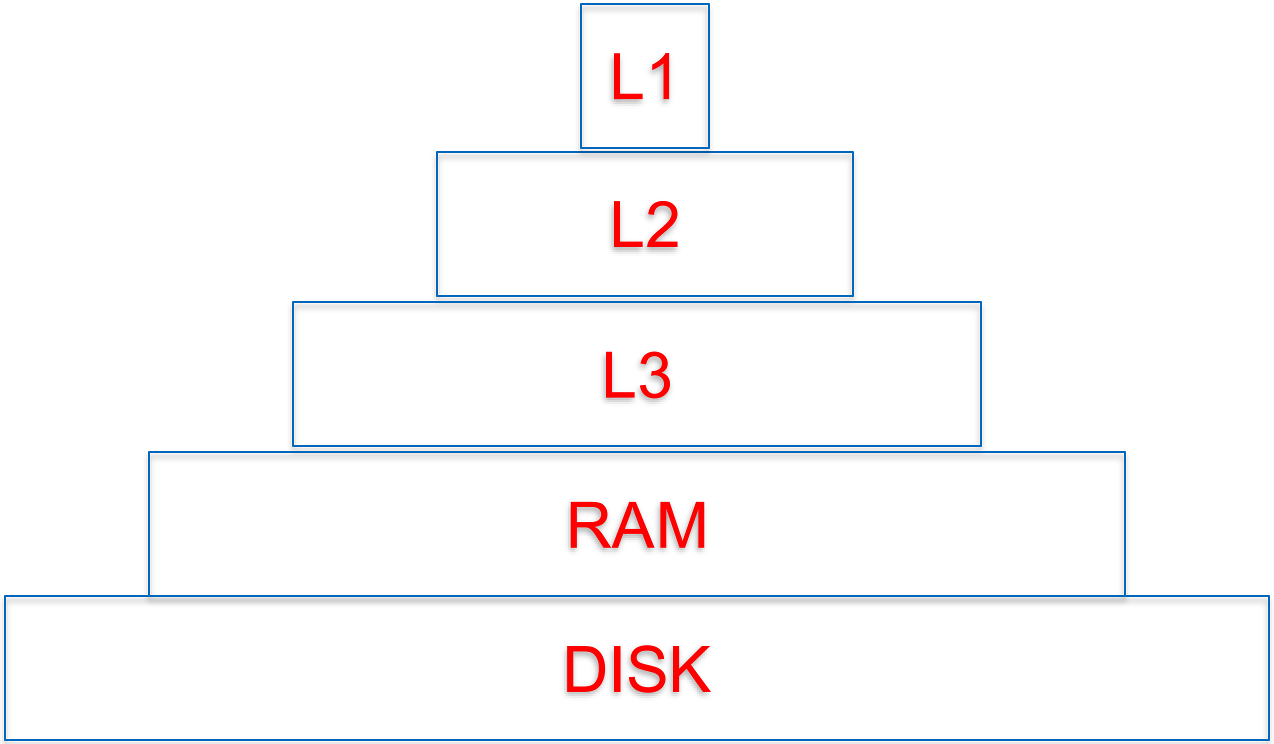
This time: **Virtual Memory & Caching**

What is Virtual Memory?

- Each process has illusion of large address space
  - 2^x bytes for x-bit addressing
- However, physical memory is usually much smaller
- How do we give this illusion to multiple processes?
  - Virtual Memory: some addresses reside in disk



Process executes from disk!



RAM is really just another layer of cache

Swapping vs. Paging

Swapping

- Loads entire process in memory
- “Swap in” (from disk) or “Swap out” (to disk) a process
- Slow (for large processes)
- Wasteful (might not require everything)
- Does not support sharing of code segments
- Virtual memory limited by size of physical memory

Paging

- Runs all processes concurrently
- A few pages from each process live in memory
- Finer granularity, higher performance
- Large virtual mem supported by small physical mem
- Certain pages (read-only ones, for example) can be shared among processes

(the contents of) **A Virtual Page Can Be**

Mapped

- to a physical frame

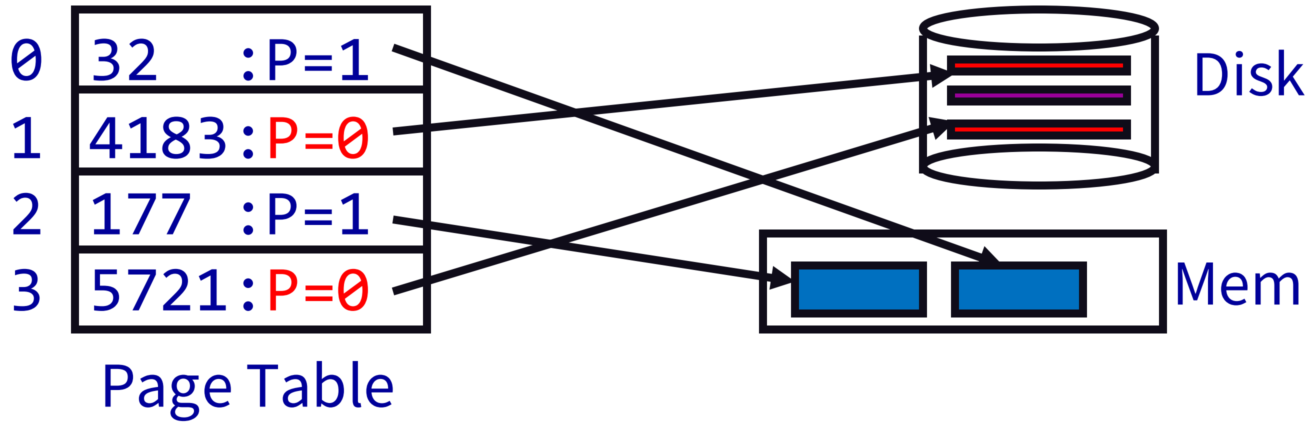
Not Mapped (→ Page Fault)

- in a physical frame, but not currently mapped
- or still in the original program file
- or zero-filled (heap/BSS, stack)
- or on backing store ("paged or swapped out")
- or illegal: not part of a segment
  → Segmentation Fault

Supporting Virtual Memory

Modify Page Tables with a *present* bit

- Page in memory → *present = 1*
- Page not in memory → PT lookup triggers **page fault**



Handling a Page Fault

Identify page and reason (r/w/x)

- access inconsistent w/ segment access rights
  → terminate process
- access a page that is kept on disk:
  → does frame with the code/data already exist?
  No? Allocate a frame & bring page in (next slide)
- access of zero-initialized data (BSS) or stack
  - Allocate a frame, fill frame with zero bytes

When a page needs to be brought in…

- Find a free frame
  - evict one if there are no free frames
- Issue disk request to fetch data for page
- Block current process
- Context switch to another process
- When disk request completes, update PTE
  - frame number, present bit, RWX bits
- Put current process in ready queue

When a frame needs to be swapped out…

- Find all page table entries that refer to the frame
  - Frame might be shared
  - Maintain a *Core Map* (frames → pages)
- Set each page table entry to not present
- Remove any TLB entries
  - “TLB Shootdown”
- Write changes on page back to disk, if needed
  - Dirty/Modified bit in PTE indicates need
  - Text segments are (still) on program image on disk

Updated Context Switch

- Save current process' registers in PCB
- ***Flush TLB*** *(unless TLB is tagged)*
- Restore registers and PTBR of next process to run
- "Return from Interrupt"

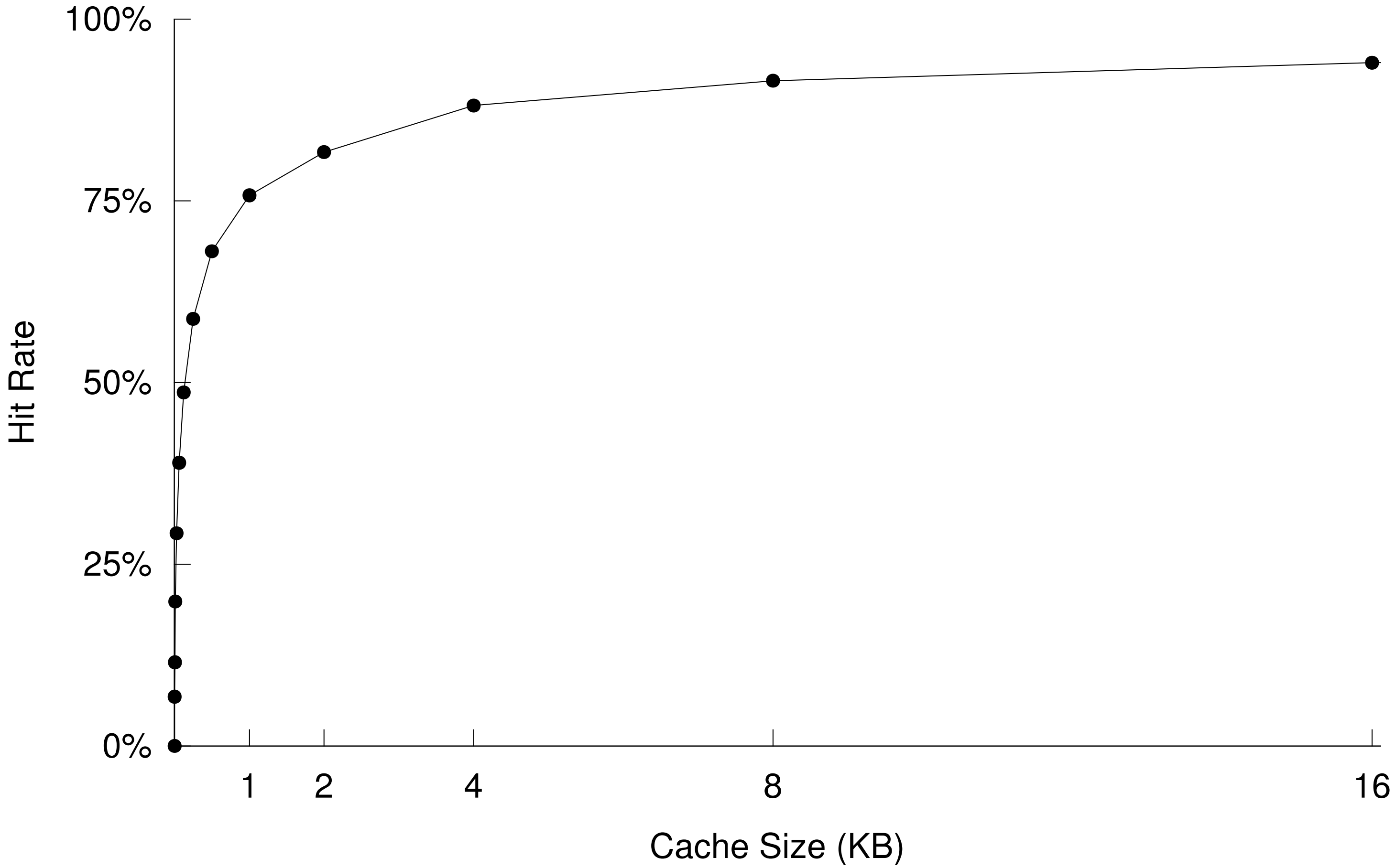
Memory Hierarchy

Cache	Hit Cost	Size
1st level cache / 1st level TLB	1 ns	64 KB
2nd level cache / 2nd level TLB	4 ns	256 KB
3rd level cache	12 ns	2 MB
Memory (DRAM)	100 ns	10 GB
Data center memory (DRAM)	100 µs	100 TB
Local non-volatile memory	100 µs	100 GB
Local disk	10 ms	1 TB
Data center disk	10 ms	100 PB
Remote data center disk	200 ms	1 XB

Every layer is a cache for the layer below it.

Working Set

1. Collection of a process' most recently used pages
   (The Working Set Model for Program Behavior, Denning,'68)
2. Pages referenced by process in last Δ time-units



Thrashing

Excessive rate of paging

Cache lines evicted before they can be reused

Causes:

- Too many processes in the system
- Cache not big enough to fit working set
- Bad luck (conflicts)
- Bad eviction policies (later)

Prevention:

- Restructure code to reduce working set
- Increase cache size
- Improve caching policies

Caching

- Assignment: where do you put the data?
- **Replacement: whom do you kick out?**

What do you do when memory is full?

Page Replacement Algorithms

- **Random:** Pick any page to eject at random
  - Used mainly for comparison
- **FIFO:** The page brought in earliest is evicted
  - Ignores usage
- **OPT:** Belady's algorithm
  - Select page not used for longest time
- **LRU:** Evict page that hasn't been used for the longest
  - Assumes past is a good predictor of the future
- **MRU:** Evict the most recently used page
- **LFU:** Evict least frequently used page
- And many approximation algorithms

Expectation

- more frames (i.e., larger cache) → *not* more misses

First-In-First-Out (FIFO) Algorithm

- *Reference string*: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- **3 frames** (3 pages in memory at a time per process):

frames

reference

reference			
1			1
2		2	1
3	3	2	1
4	3	2	4
1	3	1	4
2	2	1	4
5	2	1	5
1	2	1	5
2	2	1	5
3	2	3	5
4	4	3	5
5	4	3	5

← contents of frames after reference

page fault (miss)

hit

9 page faults

First-In-First-Out (FIFO) Algorithm

- *Reference string*: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- **4 frames** (4 pages in memory at a time per process):

frames

reference				
1				1
2			2	1
3		3	2	1
4	4	3	2	1
1	4	3	2	1
2	4	3	2	1
5	4	3	2	5
1	4	3	1	5
2	4	2	1	5
3	3	2	1	5
4	3	2	3	4
5	3	2	5	4

← contents of frames after reference

page fault

hit

10 page faults

more frames → more page faults?

Belady's Anomaly

Optimal Algorithm (OPT)

- Replace frame that will not be used for the longest
- 4 frames example

1				**1**
2			**2**	1
3		**3**	2	1
4	**4**	3	2	1
1	4	3	2	1
2	4	3	2	1
5	**5**	3	2	1
1	5	3	2	1
2	5	3	2	1
3	5	3	2	1
4	5	3	2	**4**
5	5	3	2	4

6 page faults

Question: How do we tell the future?
Answer: We can’t

OPT used as upper-bound in measuring how well your algorithm performs

OPT Approximation

In real life, we do not have access to the future page request stream of a program

→ Need to make a guess at which pages will not be used for the longest time

Least Recently Used (LRU) Algorithm

Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

1				**1**
2			**2**	1
3		**3**	2	1
4	**4**	3	2	1
1	4	3	2	1
2	4	3	2	1
5	4	**5**	2	1
1	4	5	2	1
2	4	5	2	1
3	**3**	5	2	1
4	3	**4**	2	1
5	3	4	2	**5**

page fault

hit

8 page faults

Implementing LRU

- On reference: Timestamp each page
- On eviction: Scan for oldest page

Problems:

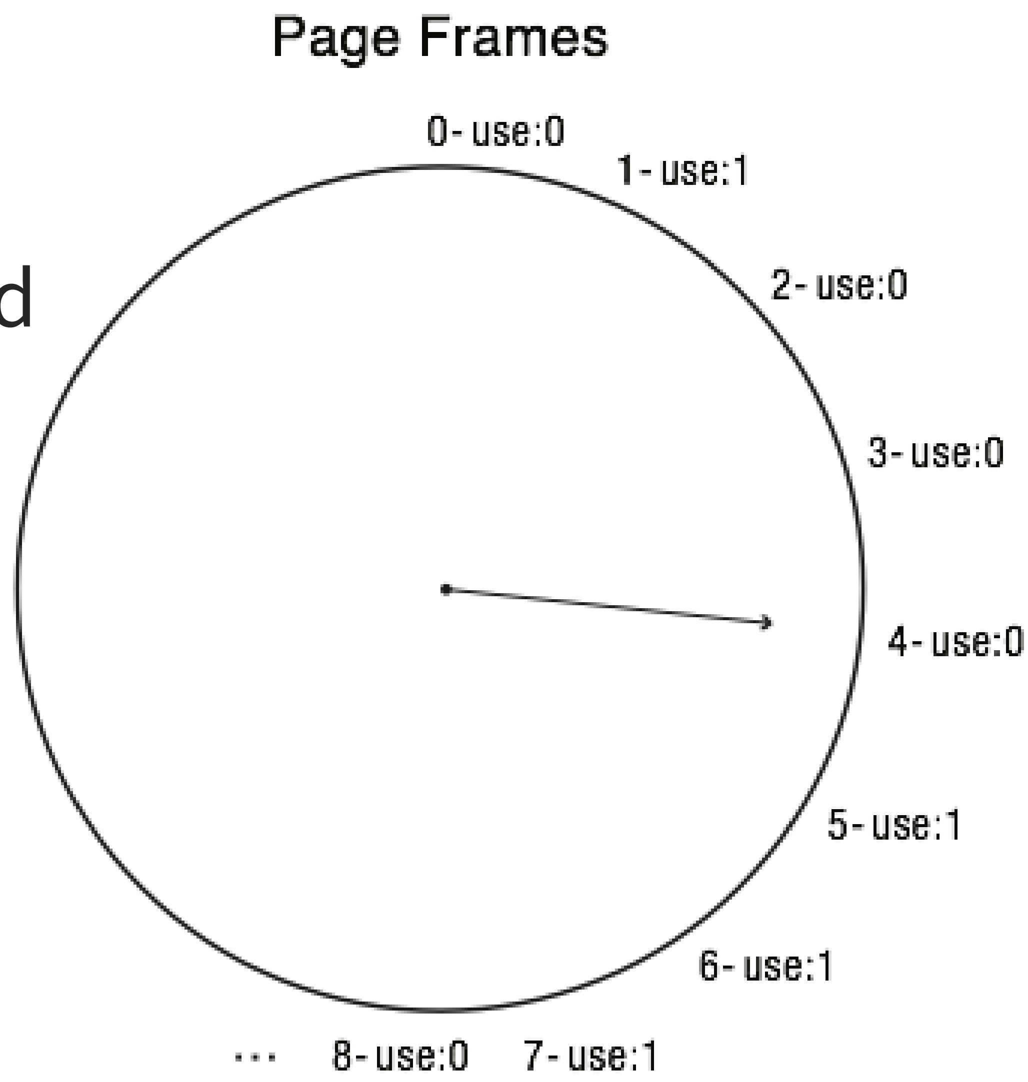
- Large page lists
- Timestamps are costly

Solution: **approximate LRU**

- Note: LRU is already an approximation
- Exploit *use* (REF) bit in PTE

Clock Algorithm

- To allocate a frame, inspect the *use* bit in the PTE at clock hand and advance clock hand
- Used? Clear *use* bit and repeat



Working Set Algorithm (WS)

- Maintain for each frame the approximate time the frame was last used
- At each clock tick
  - Update this time to the current time for all frames that were referenced since the last clock tick
    - i.e., the ones with *use* (REF) bits set
  - Clear all *use* bits
  - Put all frames that have not been used for some time Δ (working set parameter) on the free list
- When a frame is needed, use free list
  - If empty, pick any frame

Note: requires scan of all frames at each clock tick

Other Algorithms

MRU: Remove the most recently touched page

- Good for data accessed only once, *e.g.* a movie file

LFU: Remove page with lowest usage count

- Like CLOCK but use multiple bits. Shift right by 1 at regular intervals

MFU: remove the most frequently used page

Local versus Global Replacement

- So far, we have tacitly assumed that all frames are shared by all processes
  - This is called “global replacement”
- But is it fair?
  - Badly behaved processes can ruin the experience of processes with good locality
- Local replacement: divided the frames up evenly between the processes
  - Can lead to under-utilization