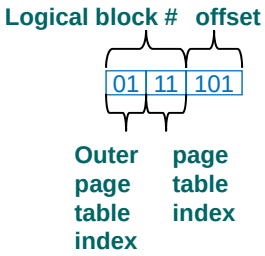
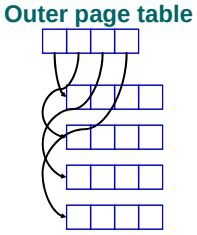
Virtual Memory Exercises

Hierarchical Page Table Exampe

Setting:

- 7 bit address space (2,2,3):
- page size 8 bytes
- 2 bytes per page table entry
  - 1 page/frame holds 4 entries
- 2 level hierarchical page table
  - 16 addressable (logical) blocks per process
- Limit: 8 physical frames per process
- LRU replacement policy
- Log. Page 0: Outer Page Table
- Log. Page 1..4: Page table
- Log Page 5+: Code/Data





At the beginning

Frame #	Content	Description	Action
0	0 0 0 0 0 0 0 0	Outer Page Table	
1			
2			
3			
4			
5			
6			
7			

Explanation

- initial configuration, nothing loaded

First action

Frame #	Content	Description	Action
0	0 0 0 0 0 0 0 0	Outer Page Table	Write("a", 68)
1			
2			
3			
4			
5			
6			
7			

Explanation

- 68=(10,00,100)=(2,0,4)
- look at MPT to locate page table 2
- not present, need to load it
- first unused frame is #1

First action

Frame #	Content	Description	Action
0	0 0 0 0 1 1 0 0	Outer Page Table	Write("a", 68)
1	0 0 0 0 0 0 0 0	Page table log page #2	
2			
3			
4			
5			
6			
7			

Explanation

- 68=(10,00,100)=(2,0,4)
- look at MPT to locate page table 2
- not present, need to load it
- first unused frame is #1
- load to frame #1
- and update MPT entry

First action

Frame #	Content	Description	Action
0	0 0 0 0 1 1 0 0	Outer Page Table	Write("a", 68)
1	0 0 0 0 0 0 0 0	Page table log. page #2	
2			
3			
4			
5			
6			
7			

Explanation

- 68=(10,00,100)=(2,0,4)
- look at MPT to locate page table 2
- not present, need to load it
- first unused frame is #1
- load to frame #1
- and update MPT entry

- look at PT2 to locate page at 0
- not present, need to load it
- first unused frame is #2

First action

Frame #	Content	Description	Action
0	0 0 0 0 1 1 0 0	Outer Page Table	Write("a", 68)
1	1 2 0 0 0 0 0 0	Page table log. page #2	
2	? ? ? ? ? ? ? ?	Data block – log page #8	
3			
4			
5			
6			
7			

Explanation

- 68=(10,00,100)=(2,0,4)
- look at MPT to locate page table 2
- not present, need to load it
- first unused frame is #1
- load to frame #1
- and update MPT entry
- look at PT2 to locate page at 0
- not present, need to load it
- first unused frame is #2
- load to frame #2
- and update PT2 entry

First action

Frame #	Content	Description	Action
0	0 0 0 0 1 1 0 0	Outer Page Table	Write("a", 68)
1	1 2 0 0 0 0 0 0	Page table log. page #2	
2	? ? ? ? a ? ? ?	Data block – log page #8	
3			
4			
5			
6			
7			

Explanation

- 68=(10,00,100)=(2,0,4)
- look at MPT to locate page table 2
- not present, need to load it
- first unused frame is #1
- load to frame #1
- and update MPT entry
- look at PT2 to locate page at 0
- not present, need to load it
- first unused frame is #2
- load to frame #2
- and update PT2 entry
- write "a" to offset 4
- **2 page faults**

Second action

Frame #	Content	Description	Action
0	0 0 0 0 1 1 0 0	Outer Page Table	Write(“a”, 68)
1	1 2 0 0 0 0 0 0	Page table log. page #2	Write (“b”,75)
2	? ? ? ? a ? ? ?	Data block – log page #8	
3			
4			
5			
6			
7			

Explanation

- 75=(10,01,011)=(2,1,3)
- look at MPT to locate page table 2
- present, at frame 1

Second action

Frame #	Content	Description	Action
0	0 0 0 0 1 1 0 0	Outer Page Table	Write(“a”, 68)
1	1 2 0 0 0 0 0 0	Page table log page #2	Write (“b”,75)
2	? ? ? ? a ? ? ?	Data block – log page #8	
3			
4			
5			
6			
7			

Explanation

- 75=(10,01,011)=(2,1,3)
- look at MPT to locate page table 2
- present, at frame 1
- look at PT2 to locate page at 1
- not present, load it to frame #3

Second action

Frame #	Content	Description	Action
0	0 0 0 0 1 1 0 0	Outer Page Table	Write("a", 68)
1	1 2 **1** **3** 0 0 0 0	Page table log page #2	Write ("b",75)
2	? ? ? ? a ? ? ?	Data block – log page #8	
3	? ? ? ? ? ? ? ?	Data block – log page #9	
4			
5			
6			
7			

Explanation

- 75=(10,01,011)=(2,1,3)
- look at MPT to locate page table 2
- present, at frame 1
- look at PT2 to locate page 1
- not present, load it to frame #3
- and update PT2 entry

Second action

Frame #	Content	Description	Action
0	0 0 0 0 1 1 0 0	Outer Page Table	Write("a", 68)
1	1 2 1 3 0 0 0 0	Page table log page #2	Write ("b",75)
2	? ? ? ? a ? ? ?	Data block – log page #8	
3	? ? ? **b** ? ? ? ?	Data block – log page #9	
4			
5			
6			
7			

Explanation

- 75=(10,01,011)=(2,1,3)
- look at MPT to locate page table 2
- present, at frame 1
- look at PT2 to locate page 1
- not present, load it to frame #3
- and update PT2 entry
- write "b" into offset 3
- 1 page fault

Third action

Frame #	Content	Description	Action
0	0 0 0 0 **1** **1** 0 0	Outer Page Table	Write(“a”, 68)
1	1 2 **1** **3** 0 0 0 0	Page table log page #2	Write (“b”,75)
2	? ? ? ? a ? ? ?	Data block – log page #8	Write(“c”,78)
3	? ? ? b ? ? **c** ?	Data block – log page #9	
4			
5			
6			
7			

Explanation

- 78=(10,01,110)=(2,1,6)
- look at MPT to locate page table 2
- present, at frame #1
- look at PT2 to locate page 1
- present, at frame #3
- write “c” into offset 6

Fourth action

Frame #	Content	Description	Action
0	0 0 **0** 0 1 1 0 0	Outer Page Table	Write(“a”, 68)
1	1 2 1 3 0 0 0 0	Page table log page #2	Write (“b”,75)
2	? ? ? ? a ? ? ?	Data block – log page #8	Write(“c”,78)
3	? ? ? b ? ? c ?	Data block – log page #9	Write(“d”,50)
4			
5			
6			
7			

Explanation

- 50=(01,10,010)=(1,2,2)
- look at MPT to locate page table 1
- not present, load it to frame #4

Fourth action

Frame #	Content	Description	Action
0	0 0 **1** **4** 1 1 0 0	Outer Page Table	Write("a", 68)
1	1 2 1 3 0 0 0 0	Page table log page #2	Write ("b",75)
2	? ? ? ? a ? ? ?	Data block – log page #8	Write("c",78)
3	? ? ? b ? ? c ?	Data block – log page #9	Write("d",50)
4	0 0 0 0 **0** 0 0 0	Page table log page #1	
5	? ? ? ? ? ? ? ?	Data block – log page #6	
6			
7			

Explanation

- 50=(01,10,010)=(1,2,2)
- look at MPT to locate page table 1
- not present, load it to frame #4 and update MPT
- look at PT1 to locate page at 2
- not present, load it to frame #5

Fourth action

Frame #	Content	Description	Action
0	0 0 1 4 1 1 0 0	Outer Page Table	Write("a", 68)
1	1 2 1 3 0 0 0 0	Page table log page #2	Write ("b",75)
2	? ? ? ? a ? ? ?	Data block – log page #8	Write("c",78)
3	? ? ? b ? ? c ?	Data block – log page #9	Write("d",50)
4	0 0 0 0 **1** **5** 0 0	Page table log page #1	
5	? ? **d** ? ? ? ? ?	Data block – log page #6	
6			
7			

Explanation

- 50=(01,10,010)=(1,2,2)
- look at MPT to locate page table 1
- not present, load it to frame #4 and update MPT
- look at PT1 to locate page at 2
- not present, load it to frame #5

- update PT1
- write "d" into offset 2
- two page faults

Fifth action

Frame #	Content	Description	Action
0	0 0 1 4 1 1 **1** **6**	Master Page Table	Write(“a”, 68)
1	1 2 1 3 0 0 0 0	Page table block #2	Write (“b”,75)
2	? ? ? ? a ? ? ?	Data block – log block #8	Write(“c”,78)
3	? ? ? b ? ? c ?	Data block – log block #9	Write(“d”,50)
4	0 0 0 0 1 5 0 0	Page table block #1	Write(“e”,125)
5	? ? **d** ? ? ? ? ?	Data block – log block #6	
6	0 0 0 0 0 0 **1** **7**	Page table block #3	
7	? ? ? ? ? **e** ? ?	Data block – log block #15	

Explanation

- 125=(11,11,101)=(3,3,5)
- look at MPT to locate page table 3
- not present, load it to frame #6 and update MPT
- look at PT3 to locate page 3
- not present, load it to frame #7
- update PT3
- write “e” into offset 5
- two page faults

Sixth action

Frame #	Content	Description	Action
0	0 0 1 4 1 1 **1** **6**	Outer Page Table	Write(“a”, 68)
1	1 2 1 3 0 0 0 0	Page table log page #2	Write (“b”,75)
2	? ? ? ? a ? ? ?	Data block – log page #8	Write(“c”,78)
3	? ? ? b ? ? c ?	Data block – log page #9	Write(“d”,50)
4	0 0 0 0 1 5 0 0	Page table log page #1	Write(“e”,125)
5	? ? **d** ? ? ? ? ?	Data block – log page #6	Write(“f”,97);
6	**0** 0 0 0 0 0 1 7	Page table log page #3	
7	? ? ? ? ? **e** ? ?	Data block – log page #15	

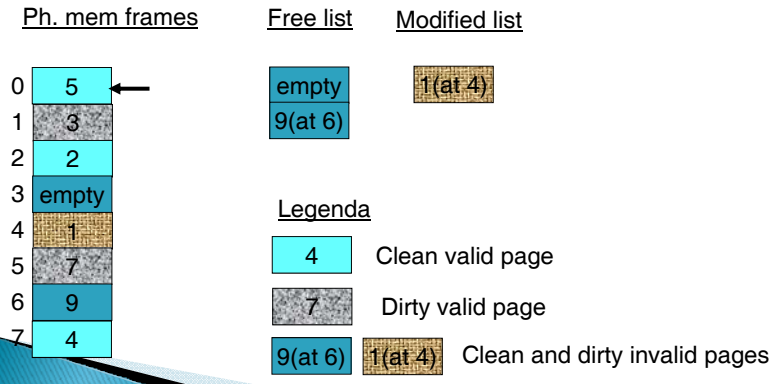
Explanation

- 97=(11,00,001)=(3,0,1)
- look at MPT to locate PT 3
- present, located in frame #6
- look at PT3 to locate page at 0
- not present, no free frames remaining, need to evict one
- LRU - the oldest frames are #1, #2
- #1 is PT, choose #2

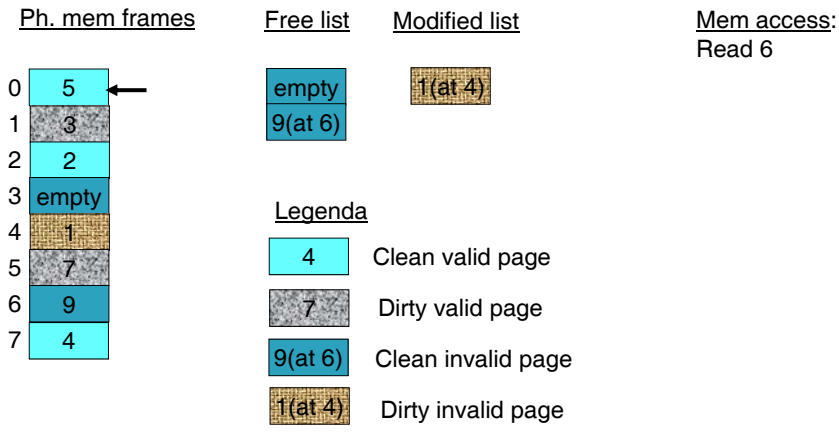
Frame #	Last access	Note
0	6	OPT, locked
1	1	PT2
2	1	data
3	3	data
4	4	PT1
5	4	data
6	5	PT3
7	5	data

Page Buffering Example

- Frames of physical memory: 8
- Buffer size: 3
- Therefore, only 5 pages are kept as valid



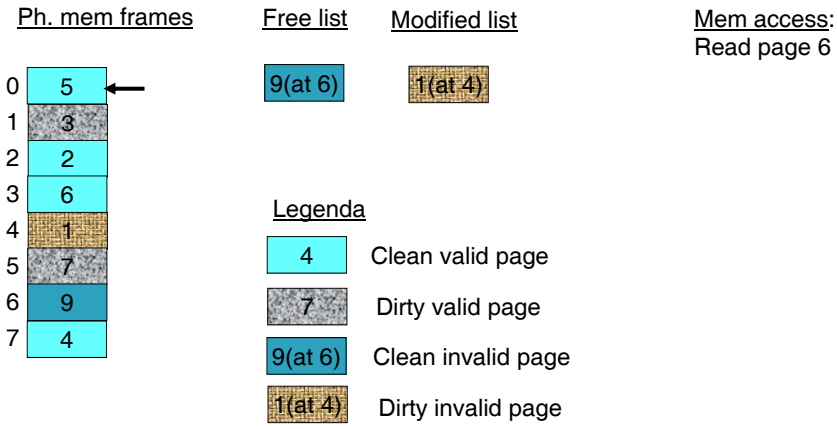
Page Buffering Example



Actions:

Read page 6 into first free block (3)

Page Buffering Example

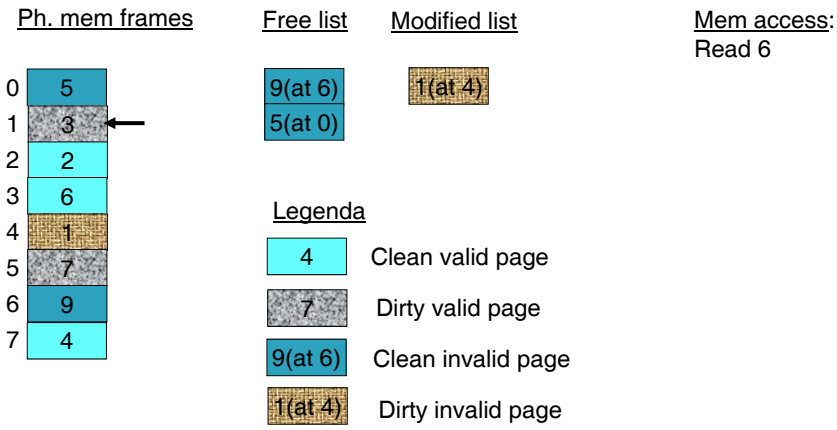


Actions:

Read page 6 into first free block (3)

Page out frame 0 (to maintain the number of invalid pages to 3)

Page Buffering Example

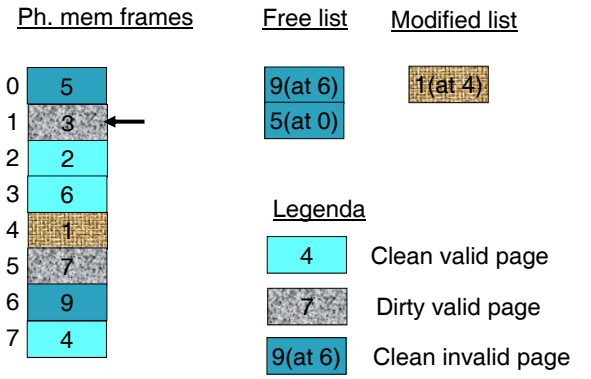


Actions:

Read page 6 into first free block (3)

Page out frame 0 (to maintain the number of invalid pages to 3)

Page Buffering Example



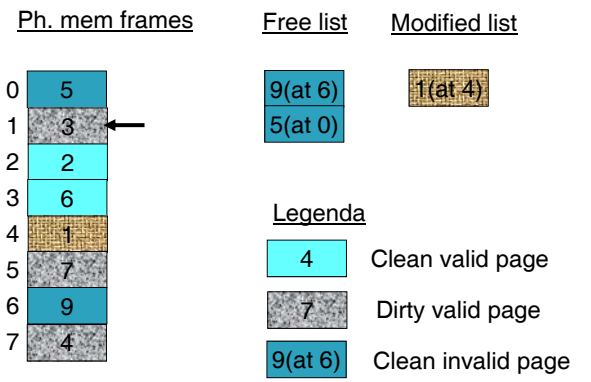
Mem access:
Read 6
Write 4

Legenda

- 4 — Clean valid page
- 7 — Dirty valid page
- 9(at 6) — Clean invalid page
- 1(at 4) — Dirty invalid page

Actions:
No page fault

Page Buffering Example



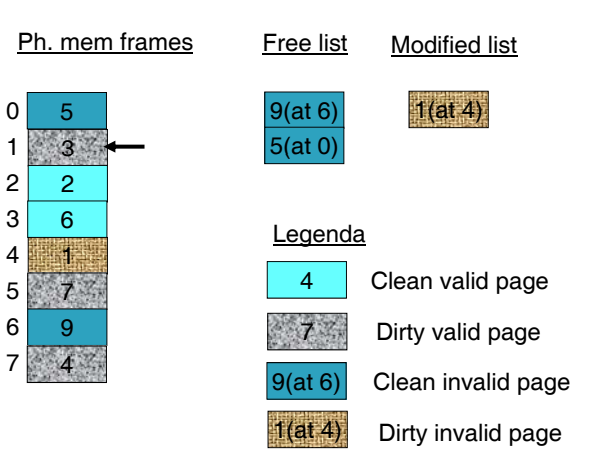
Mem access:
Read 6
Write 4

Legenda

- 4 — Clean valid page
- 7 — Dirty valid page
- 9(at 6) — Clean invalid page
- 1(at 4) — Dirty invalid page

Actions:
No page fault…
…but frame 4 is made dirty

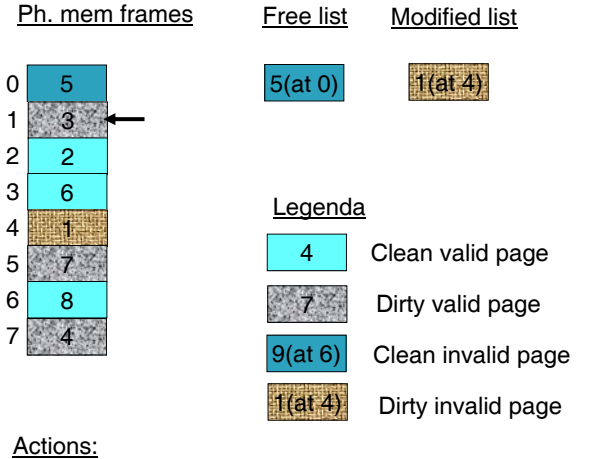
Page Buffering Example



Mem access:
Read 6
Write 4
Read 8

Actions:
page fault, put 8 into the first free frame

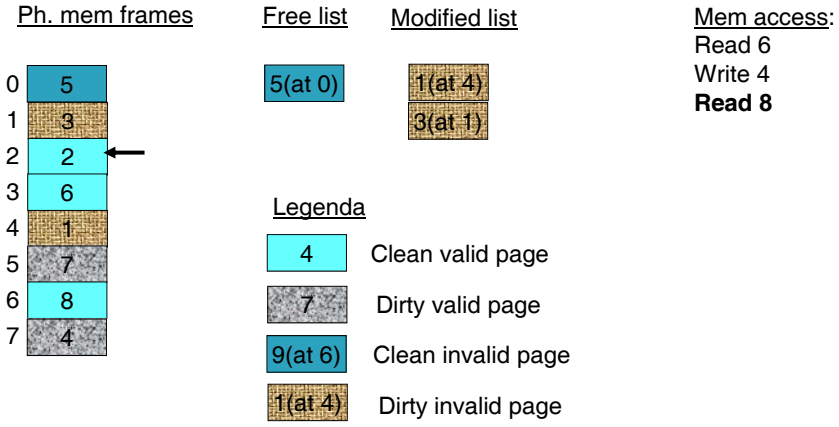
Page Buffering Example



Mem access:
Read 6
Write 4
Read 8

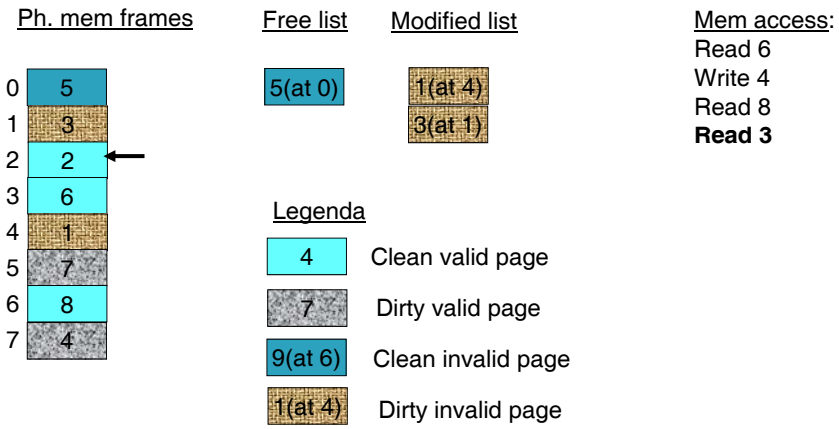
Actions:
page fault, put 8 into the first free frame (which was frame 8)
Now evict one page to maintain buffer size 3

Page Buffering Example



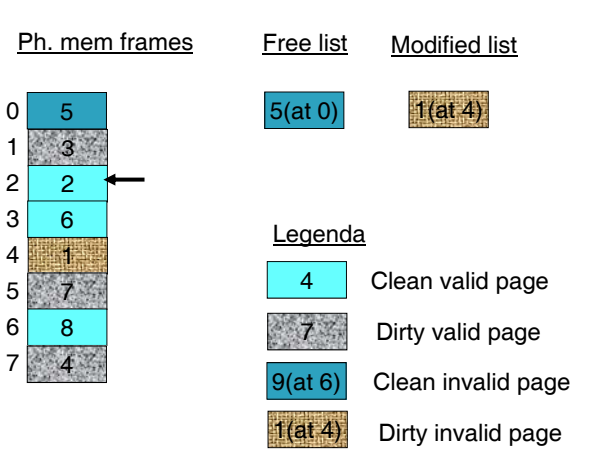
Actions:
page fault, put 8 into the first free frame (which was frame 8)
Now evict one page to maintain buffer size 3

Page Buffering Example



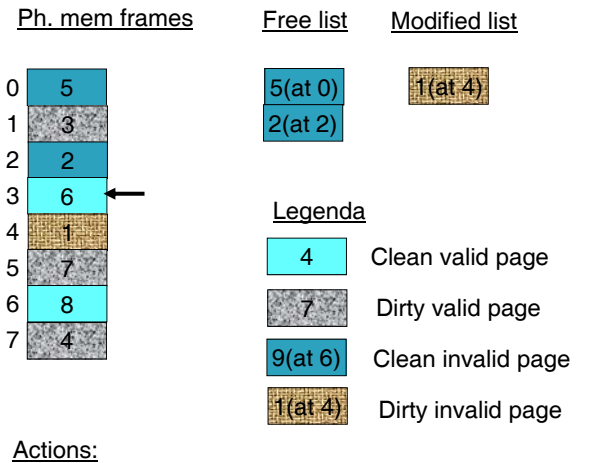
Actions:
Is there a page fault? Do we need to go to disc?

Page Buffering Example



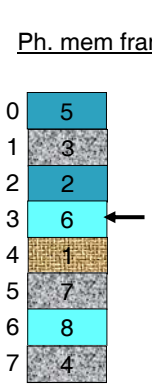
Actions:
Page 3 is recovered from the modified list

Page Buffering Example



Actions:
Page 3 is recovered from the modified list
But we will evict page 2 to maintain buffer size 3

Page Buffering Example



Free list: 5(at 0), 2(at 2)

Modified list: 1(at 4)

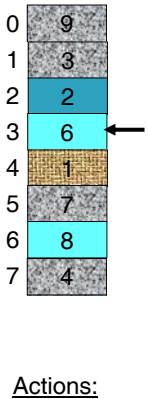
Mem access:
Read 6
Write 4
Read 8
Read 3
Write 9

Legenda

4	Clean valid page
7	Dirty valid page
9(at 6)	Clean invalid page
1(at 4)	Dirty invalid page

Actions:
Page fault, put 9 into first free frame (0)

Page Buffering Example



Free list: 2(at 2)

Modified list: 1(at 4)

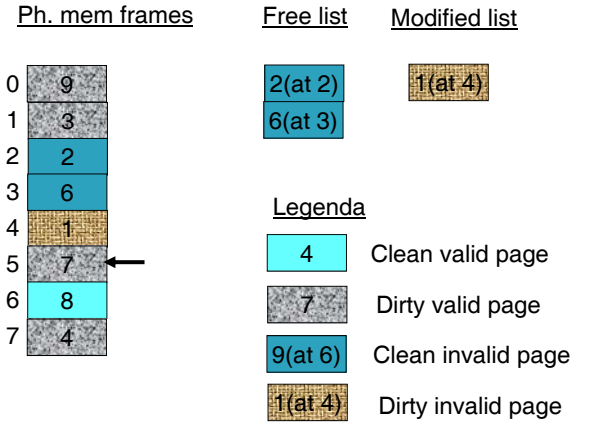
Mem access:
Read 6
Write 4
Read 8
Read 3
Write 9

Legenda

4	Clean valid page
7	Dirty valid page
9(at 6)	Clean invalid page
1(at 4)	Dirty invalid page

Actions:
Page fault, put 9 into first free frame (0)
and evict page 6 from frame 3 to maintain buffer size

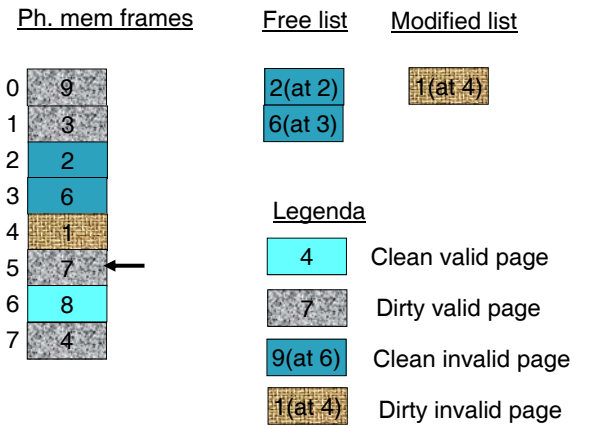
Page Buffering Example



Mem access:
Read 6
Write 4
Read 8
Read 3
Write 9

Actions:
Page fault, put 9 into first free frame (0)
and evict page 6 from frame 3 to maintain buffer size

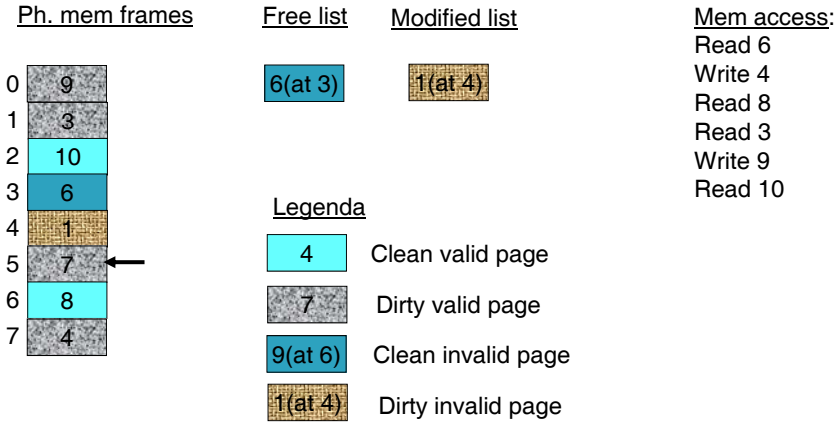
Page Buffering Example



Mem access:
Read 6
Write 4
Read 8
Read 3
Write 9
Write 10

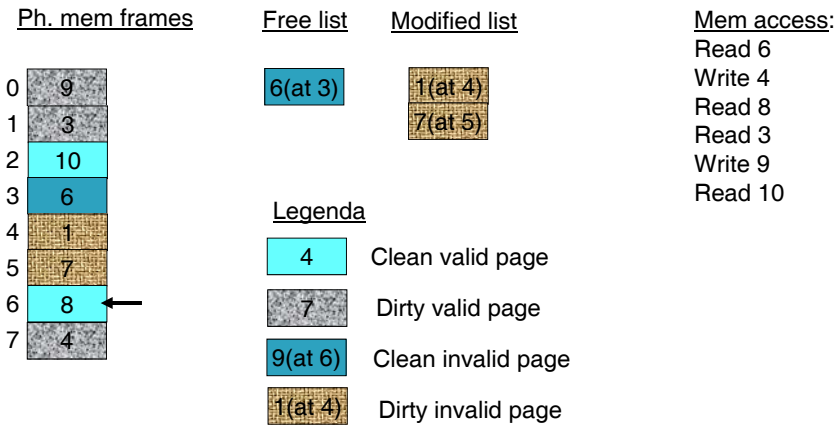
Actions:
Page fault, put 10 into first free frame (2)

Page Buffering Example



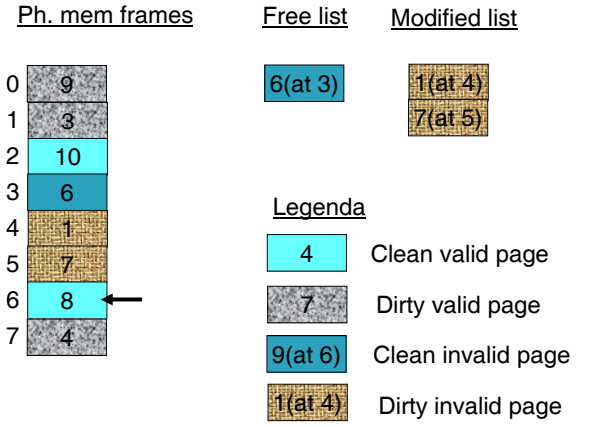
Actions:
Page fault, put 10 into first free frame (2) …
… and evict page 7 from frame 5 to maintain buffer size

Page Buffering Example



Actions:
Page fault, put 10 into first free frame (2) …
… and evict page 7 from frame 5 to maintain buffer size

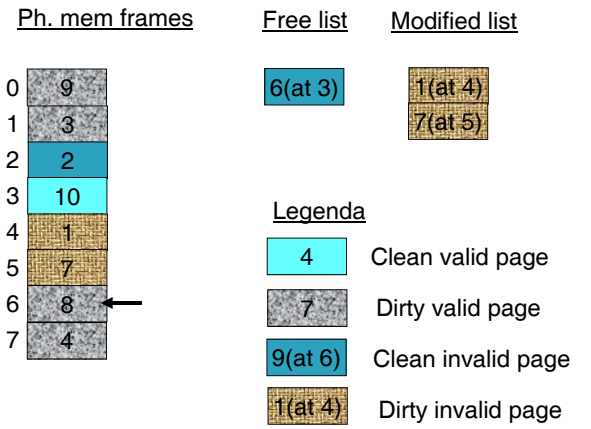
Page Buffering Example



Mem access:
Read 6
Write 4
Read 8
Read 3
Write 9
Read 10
Write 8

Actions:
No page fault, but make frame 8 dirty

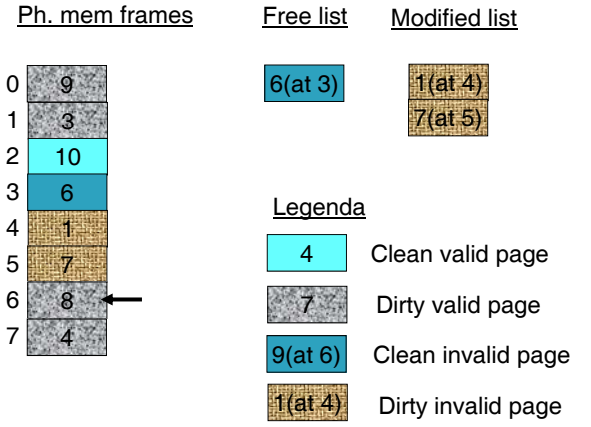
Page Buffering Example



Mem access:
Read 6
Write 4
Read 8
Read 3
Write 9
Read 10
Write 8

Actions:
No page fault, but make frame 6 dirty

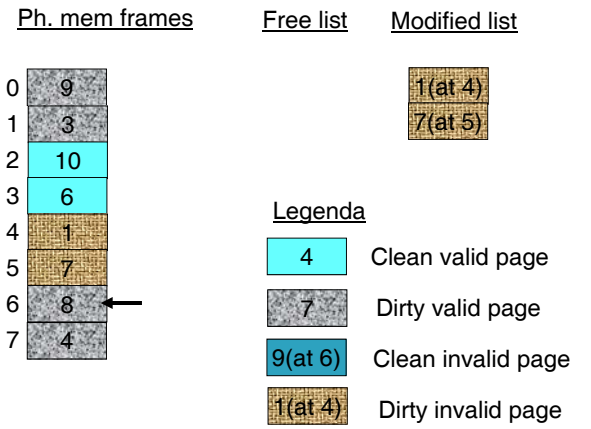
Page Buffering Example



Mem access:
Read 6
Write 4
Read 8
Read 3
Write 9
Read 10
Write 8
Read 6

Actions:
Page 6 recovered from the buffer

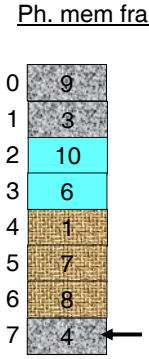
Page Buffering Example



Mem access:
Read 6
Write 4
Read 8
Read 3
Write 9
Read 10
Write 8
Read 6

Actions:
Page 6 recovered from the buffer …
… evict page 8 from frame 6 to maintain buffer size

Page Buffering Example



Free list

Modified list

1(at 4)
7(at 5)
8(at 6)

Legenda

4 Clean valid page

7 Dirty valid page

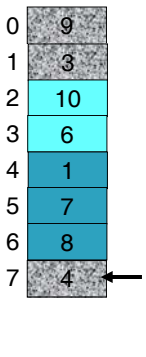
9(at 6) Clean invalid page

1(at 4) Dirty invalid page

Mem access:
Read 6
Write 4
Read 8
Read 3
Write 9
Read 10
Write 8
Read 6

Actions:
Free list is empty, time to clean (write to disc) the modified list

Page Buffering Example



Free list

1(at 4)
7(at 5)
8(at 6)

Modified list

Legenda

4 Clean valid page

7 Dirty valid page

9(at 6) Clean invalid page

1(at 4) Dirty invalid page

Mem access:
Read 6
Write 4
Read 8
Read 3
Write 9
Read 10
Write 8
Read 6

Actions:
Free list is empty, time to clean (write to disc) the modified list

In reality, you would want to clean the modified list before the free list becomes empty.