



## Discussion 6

Paging, Caches

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03/08/24

Staff

# Announcements

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
		Homework 3 Due	Homework 4 Release		Project 2 Design Due	
Midterm 2 Conflict Due				Midterm 2 (8:00 pm - 10:00 pm)		

# Paging

# Page Tables

Allocate memory in fixed-size chunks called **pages**.

**Page table** is indexed by **virtual page number (VPN)**.

- Each entry is called the **page table entry (PTE)** which contains the **physical page number (PPN)** and metadata.
- Page tables also reside in memory.
- Typically (but not always) a page table will fit into a single page.
- Each process has its own page table. **Page table base register** (PTBR) contains the starting address of the page table for that process (e.g. CR3 register for x86).
- Metadata stores bits such as valid, dirty, writable, and more.

Virtual Address	
Virtual Page Number (VPN)	Offset

Page Table	
PPN	Metadata

Physical Address	
Physical Page Number (PPN)	Offset

# Page Tables

Assumes **byte addressable** system where each bit addresses one byte.

# virtual address bits = # virtual page number bits + # offset bits

# physical address bits = # physical page number bits + # offset bits

# virtual pages =  $2^{\text{\# virtual page number bits}}$

# physical pages =  $2^{\text{\# physical page number bits}}$

page size (in bytes) =  $2^{\text{\# offset bits}}$

virtual memory size (in bytes) = # virtual pages  $\times$  page size (in bytes)

physical memory size (in bytes) = # physical pages  $\times$  page size (in bytes)

# page table entries = # virtual pages

# page table entry bits = # physical page number bits + # metadata bits

page table entry size (in bytes) = # page table entry bits  $\div$  8

page table size (in bytes) = # page table entries  $\times$  page table entry size (in bytes)

Virtual Address	
Virtual Page Number (VPN)	Offset

Page Table	
PPN	Metadata

Physical Address	
Physical Page Number (PPN)	Offset

# Translation Lookaside Buffer (TLB)

**Translation lookaside buffer (TLB)** is a small *hardware* table containing results of recent address translations.

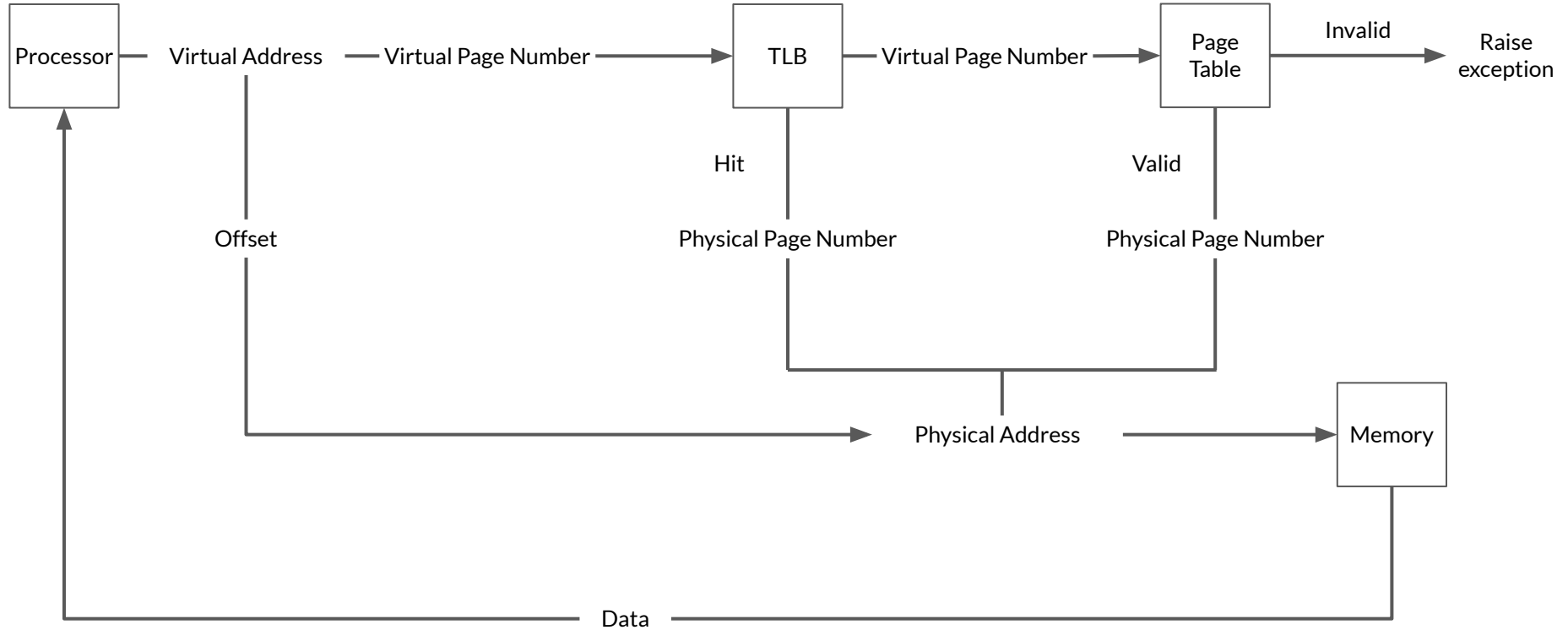
- Can be thought of as a cache, generally fully associative.
- Virtual page number is the tag.
- Stores address translations *not the actual data* (i.e. cache for page table).
- Generally part of the MMU.

Virtual Address	
Virtual Page Number (VPN)	Offset

Translation Lookaside Buffer		
Tag	Data	
VPN	PPN	Metadata

Physical Address	
Physical Page Number (PPN)	Offset

# Translation Lookaside Buffer (TLB)



# Demand Paging

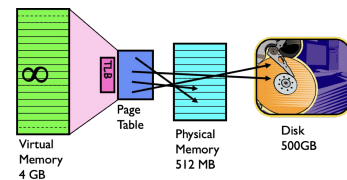
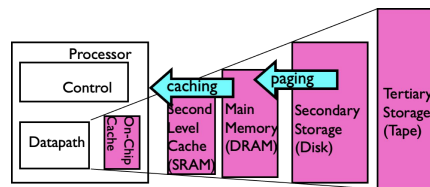
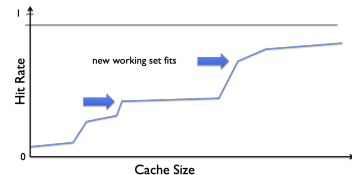
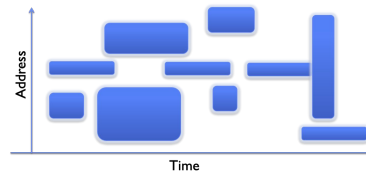
**Working set** is the subset of the address space used during execution.

**Demand paging** is the idea of storing certain working sets on disks and bringing them into memory as necessary.

- Allows for bigger virtual address space than physical memory can provide.
- **Resident set** is the subset of the address space being held in memory.
- **Thrashing** happens when memory is too small for working set and replacements need to frequently happen.

**Page fault** occurs when a program attempts to access virtual address not currently located in physical memory.

1. MMU traps to the kernel and saves current state information.
2. Kernel finds out which virtual page was needed (e.g. CR2 in x86).
3. Check if virtual address is valid. Use page replacement policy to remove a page from physical memory and write it to disk.
4. Bring in the page corresponding to the virtual address from disk (e.g. swap map in Linux) and update the page table entry.
5. Restore saved state from (1) and resume execution.



# Concept Check

1. True or False: The page table base pointer contains the virtual address of the page table.
2. True or False: If a user process accesses an address that generates a page fault, the OS will terminate this process for access violation.
3. What are some advantages of having a larger page size? What about its disadvantages?

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**False. The CR3 register contains its physical address. If it were virtually addressed, it would have to go through address translation, but then you run into the problem of having to know where the page table is located in physical memory.**
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**False. A page fault can mean many things: this memory can be just unmapped or previously mapped but not resident in main memory at the time of access. The OS can handle such cases appropriately and map a new page in the user address space.**
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3. What are some advantages of having a larger page size? What about its disadvantages?  
**Having a larger page size would decrease the number of page table entries and thus the size of the page table. It could also potentially improve TLB performance as a result. Its main disadvantage is internal fragmentation.**

# Little Page Translation

The following table shows the 4 entries in the page table. Recall that the valid bit is 1 if the page is resident in physical memory and 0 if the page is on disk or hasn't been allocated.

	Valid	PPN
0	0	7
1	1	9
2	0	3
3	1	2

If there are 1024 bytes per page, what is the physical address corresponding to the virtual address 0xF74?

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The following table shows the 4 entries in the page table. Recall that the valid bit is 1 if the page is resident in physical memory and 0 if the page is on disk or hasn't been allocated.

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$$\begin{aligned}\# \text{ offset bits} &= \log_2(\text{page size}) \\ &= \log_2(1024) \\ &= 10\end{aligned}$$

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	Virtual Address											
0x	F				7				4			
0b	1	1	1	1	0	1	1	1	0	1	0	0
	VPN			Offset								

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0b	1	1	1	1	0	1	1	1	0	1	0	0
	VPN			Offset								

Diagram illustrating the structure of a 32-bit Physical Address:

- The address is divided into two main fields: **PPN** (Physical Page Number) and **Offset**.
- The **PPN** field is 16 bits wide and is further divided into a 2-bit field (labeled 1 and 0) and a 14-bit field.
- The **Offset** field is 16 bits wide.

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	VPN		Offset									

	Physical Address											
0x	B				7				4			
0b	1	0	1	1	0	1	1	1	0	1	0	0
	PPN				Offset							

# Demand Pages

An up-and-coming big data startup has just hired you to help design their new memory system for a byte- addressable system. Suppose the virtual and physical memory address space is 32 bits with a 4KB page size.

1. Suppose you know that there will only be 4 processes running at the same time, each with a Resident Set Size (RSS) of 512MB and a working set size of 256KB. What is the minimum amount of TLB entries that your system would need to support to be able to map/cache the working set size for one process? What happens if you have more entries? What about if you have fewer entries?
2. Suppose you run some benchmarks on the system and you see that the system is utilizing over 99% of its paging disk IO capacity, but only 10% of its CPU. What is a combination of the of disk space and memory size that can cause this to occur? Assume you have TLB entries equal to the answer from the previous part.
3. Out of increasing the size of the TLB, adding more disk space, and adding more memory, which one would lead to the largest performance increase and why?

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Working set size 256 KB = 64 pages → TLB needs 64 entries.

More entries → performance increases since process has changing working sets.

Fewer entries → performance suffers since it can't easily translate addresses in the working set.

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System is thrashing → not enough memory to fit the working-set in memory without page faulting .

Regardless of disk space or TLB size, demand paging will take place as long as physical memory size is  $< 4 \times 512 \text{ MB} = 2 \text{ GB}$ .

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[Add more memory to avoid demand paging.](#)

# Caches

# Caches

**Cache** contains a copy of data that can be accessed more quickly than the original.

- Exploits different types of locality to quickly access data.
- **Temporal locality** is when programs tend to reference same data that was recently accessed.
- **Spatial locality** is when programs tend to reference data near other data that was recently accessed.

**Average memory access time (AMAT)** = Hit Rate  $\times$  Hit Time + Miss Rate  $\times$  Miss Time

# Replacement Policies

**First in First Out (FIFO)** evicts page that has been in memory the longest.

- Somewhat fair since each page spends a roughly equal amount of time before eviction.
- Worst performance for cycling through an array bigger than cache.

**Minimum (MIN)** replaces pages used farthest in the future.

- Provably optimal for minimizing misses.
- Requires knowledge of the future.

**Least recently used (LRU)** evicts pages that hasn't been used for the longest time.

- Exploits temporal locality to predict the future.
- Costly implementation (e.g. linked lists), especially in hardware.
- Approximates MIN but not always optimal.

**Belady's anomaly** states that increasing cache capacity can actually *increase* the miss rate.

- Applies to algorithms that don't have the **stack property** which states that the set of pages with cache size  $n \subseteq$  set of pages with cache size  $n + 1$ .
- FIFO is not a stack algorithm, MIN and LRU are.

FIFO												
	A	B	C	D	A	B	E	A	B	C	D	E
1	A			D			E					+
2		B			A			+		C		
3			C			B			+		D	

LRU												
	A	B	C	D	A	B	E	A	B	C	D	E
1	A			D			E			C		E
2		B			A			+			D	
3			C			B			+			

MIN												
	A	B	C	D	A	B	E	A	B	C	D	E
1	A				+			+		C	D	
2		B				+			+			
3			C	D			E					+

# Replacement Policies

FIFO												
	A	B	C	D	A	B	E	A	B	C	D	E
1	A			D			E					+
2		B			A			+		C		
3			C			B			+		D	

LRU												
	A	B	C	D	A	B	E	A	B	C	D	E
1	A			D			E			C		E
2		B			A			+			D	
3			C			B			+			

MIN												
	A	B	C	D	A	B	E	A	B	C	D	E
1	A				+			+		C	D	
2		B				+			+			
3			C	D			E					+

FIFO												
	A	B	C	D	A	B	E	A	B	C	D	E
1	A				+		E				D	
2		B				+		A				E
3			C						B			
4				D						C		

LRU												
	A	B	C	D	A	B	E	A	B	C	D	E
1	A				+			+				E
2		B				+			+			
3			C				E				D	
4				D						C		

MIN												
	A	B	C	D	A	B	E	A	B	C	D	E
1	A				+			+			D	
2		B				+			+			
3			C							+		
4				D			E					+

# Translation Trivia

1. Consider a machine with a physical memory of 8 GiB, a page size of 8 KiB, and a page table entry size of 4 bytes. How many levels of page tables would be required to map a 46-bit virtual address space if every page table fits into a single page?
2. List the fields of a page table entry (PTE) in your scheme.

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$$\begin{aligned}\text{\# bytes that can be mapped using a page table} &= \text{\# pages pointed to by page table} \times \text{page size} \\ &= (\text{size of page table} \div \text{size of PTE}) \times \text{page size} \\ &= 2^{13} \div 2^2 \times 2^{13} \\ &= 2^{24} \text{ bytes}\end{aligned}$$

Byte addressable means each byte is addressed by one bit in the virtual address.

One level  $\rightarrow 2^{24}$  bytes

Two levels  $\rightarrow 2^{35}$  bytes

Three levels  $\rightarrow 2^{46}$  bytes

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2. List the fields of a page table entry (PTE) in your scheme.

$$\begin{aligned}\text{\# PPN bits} &= \log_2(\text{\# physical pages}) \\ &= \log_2(\text{physical memory size} \div \text{page size}) \\ &= \log_2(2^{33} \div 2^{13}) \\ &= 20 \text{ bits}\end{aligned}$$

$$\text{\# metadata bits} = \text{\# PTE bits} - \text{\# PPN bits} = 12 \text{ bits}$$

# Translation Trivia

3. Without a cache or TLB, how many memory operations are required to read or write a single 32-bit word?
4. With a TLB, how many memory operations can this be reduced to? Best-case scenario? Worst-case scenario?

# Translation Trivia

3. Without a cache or TLB, how many memory operations are required to read or write a single 32-bit word?  
3 page table lookups + 1 data access = 4
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3. Without a cache or TLB, how many memory operations are required to read or write a single 32-bit word?  
3 page table lookups + 1 data access = 4
  
4. With a TLB, how many memory operations can this be reduced to? Best-case scenario? Worst-case scenario?  
TLB access does not count as memory operation.  
Best case: 1 data access  
Worst case: 3 page table lookups + 1 data access = 4

# Translation Trivia

5. Consider a machine with a page size of 1024 bytes. There are 8KB of physical memory and 8KB of virtual memory. The TLB is a fully associative cache with space for 4 entries that is currently empty. Assume that the physical page number is always one more than the virtual page number. This is a sequence of memory address accesses for a program we are writing:

0x294, 0xA76, 0x5A4, 0x923, 0xCFF, 0xA12, 0xF9F, 0x392, 0x341.

How many TLB hits and page faults are there? What are the contents of the TLB at the end of the sequence?

$$\begin{aligned}\# \text{ offset bits} &= \log_2(\text{page size}) \\ &= \log_2(1024) \\ &= 10\end{aligned}$$

TLB hits	0
Page Faults	0

Page Table		
	Valid	PPN
0	0	NULL
1	1	2
2	0	NULL
3	0	4
4	0	5
5	1	6
6	1	7
7	0	NULL

TLB		
Tag	PPN	Valid
NULL	NULL	0
NULL	NULL	0
NULL	NULL	0
NULL	NULL	0

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Virtual Address												
0x	2			9				4				
0b	0	0	0	1	0	1	0	0	1	0	1	0
VPN				Offset								

TLB		
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# offset bits =  $\log_2(\text{page size})$   
=  $\log_2(1024)$   
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TLB hits	0
Page Faults	1

Page Table		
	Valid	PPN
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TLB hits	0
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Page Table		
	Valid	PPN
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4	0	5
5	1	6
6	1	7
7	0	NULL

		Virtual Address												
0x		2			9				4					
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		VPN			Offset									

TLB		
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Page Faults	1

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	Virtual Address												
0x	A				7				6				
0b	0	1	0	1	0	0	1	1	1	0	1	1	0
	VPN				Offset								

TLB		
Tag	PPN	Valid
0	1	1
NULL	NULL	0
NULL	NULL	0
NULL	NULL	0

# Translation Trivia

5. Consider a machine with a page size of 1024 bytes. There are 8KB of physical memory and 8KB of virtual memory. The TLB is a fully associative cache with space for 4 entries that is currently empty. Assume that the physical page number is always one more than the virtual page number. This is a sequence of memory address accesses for a program we are writing:

0x294, 0xA76, 0x5A4, 0x923, 0xCFF, 0xA12, 0xF9F, 0x392, 0x341.

How many TLB hits and page faults are there? What are the contents of the TLB at the end of the sequence?

# offset bits =  $\log_2(\text{page size})$   
=  $\log_2(1024)$   
= 10

TLB hits	0
Page Faults	2

Page Table		
	Valid	PPN
0	1	1
1	1	2
2	0	NULL
3	0	4
4	0	5
5	1	6
6	1	7
7	0	NULL

		Virtual Address												
0x		A				7				6				
0b		0	1	0	1	0	0	1	1	1	0	1	1	0
		VPN				Offset								

TLB		
Tag	PPN	Valid
0	1	1
NULL	NULL	0
NULL	NULL	0
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$$\begin{aligned}\# \text{ offset bits} &= \log_2(\text{page size}) \\ &= \log_2(1024) \\ &= 10\end{aligned}$$

TLB hits	0
Page Faults	2

Page Table		
	Valid	PPN
0	1	1
1	1	2
2	1	3
3	0	4
4	0	5
5	1	6
6	1	7
7	0	NULL

		Virtual Address												
0x		A				7				6				
0b		0	1	0	1	0	0	1	1	1	0	1	1	0
		VPN				Offset								

TLB		
Tag	PPN	Valid
0	1	1
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0	1	1
1	1	2
2	1	3
3	0	4
4	0	5
5	1	6
6	1	7
7	0	NULL

Virtual Address												
0x	5					A				4		
0b	0	0	1	0	1	1	0	1	0	0	1	0
VPN					Offset							

TLB		
Tag	PPN	Valid
0	1	1
2	3	1
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1	1	2
2	1	3
3	0	4
4	0	5
5	1	6
6	1	7
7	0	NULL

		Virtual Address													
0x		5				A				4					
0b		0	0	1	0	1	1	0	1	0	0	1	0	0	
		VPN				Offset									

TLB		
Tag	PPN	Valid
0	1	1
2	3	1
1	2	1
NULL	NULL	0

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0	1	1
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2	1	3
3	0	4
4	0	5
5	1	6
6	1	7
7	0	NULL

Virtual Address												
0x	9					2				3		
0b	0	1	0	0	1	0	0	1	0	0	0	1
VPN					Offset							

TLB		
Tag	PPN	Valid
0	1	1
2	3	1
1	2	1
NULL	NULL	0

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=  $\log_2(1024)$   
= 10

TLB hits	1
Page Faults	2

Page Table		
	Valid	PPN
0	1	1
1	1	2
2	1	3
3	0	4
4	0	5
5	1	6
6	1	7
7	0	NULL

Virtual Address													
0x	9			2			3						
0b	0	1	0	0	1	0	0	1	0	0	0	1	1
VPN				Offset									

TLB		
Tag	PPN	Valid
0	1	1
2	3	1
1	2	1
NULL	NULL	0

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Page Table		
	Valid	PPN
0	1	1
1	1	2
2	1	3
3	0	4
4	0	5
5	1	6
6	1	7
7	0	NULL

Virtual Address												
0x	C				F				F			
0b	0	1	1	0	0	1	1	1	1	1	1	1
VPN					Offset							

TLB		
Tag	PPN	Valid
0	1	1
2	3	1
1	2	1
NULL	NULL	0

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1	1	2
2	1	3
3	0	4
4	0	5
5	1	6
6	1	7
7	0	NULL

		Virtual Address											
0x		C				F				F			
0b		0	1	1	0	0	1	1	1	1	1	1	1
		VPN				Offset							

TLB		
Tag	PPN	Valid
0	1	1
2	3	1
1	2	1
NULL	NULL	0

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0	1	1
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5	1	6
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		Virtual Address											
0x		C				F				F			
0b		0	1	1	0	0	1	1	1	1	1	1	1
		VPN				Offset							

TLB		
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0	1	1
2	3	1
1	2	1
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# offset bits =  $\log_2(\text{page size})$   
=  $\log_2(1024)$   
= 10

TLB hits	1
Page Faults	3

Page Table		
	Valid	PPN
0	1	1
1	1	2
2	1	3
3	1	4
4	0	5
5	1	6
6	1	7
7	0	NULL

		Virtual Address												
0x		A					1				2			
0b		0	1	0	1	0	0	0	0	1	0	0	1	0
		VPN					Offset							

TLB		
Tag	PPN	Valid
0	1	1
2	3	1
1	2	1
3	4	1

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How many TLB hits and page faults are there? What are the contents of the TLB at the end of the sequence?

# offset bits =  $\log_2(\text{page size})$   
=  $\log_2(1024)$   
= 10

TLB hits	2
Page Faults	3

Page Table		
	Valid	PPN
0	1	1
1	1	2
2	1	3
3	1	4
4	0	5
5	1	6
6	1	7
7	0	NULL

Virtual Address												
0x	A			1			2					
0b	0	1	0	1	0	0	0	0	1	0	0	1
VPN				Offset								

TLB		
Tag	PPN	Valid
0	1	1
2	3	1
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3	4	1

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Page Table		
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0	1	1
1	1	2
2	1	3
3	1	4
4	0	5
5	1	6
6	1	7
7	0	NULL

Virtual Address												
0x	F					9				F		
0b	0	1	1	1	1	1	0	0	1	1	1	1
VPN						Offset						

TLB		
Tag	PPN	Valid
0	1	1
2	3	1
1	2	1
3	4	1

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# offset bits =  $\log_2(\text{page size})$   
=  $\log_2(1024)$   
= 10

TLB hits	3
Page Faults	3

Page Table		
	Valid	PPN
0	1	1
1	1	2
2	1	3
3	1	4
4	0	5
5	1	6
6	1	7
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Virtual Address													
0x	F			9				F					
0b	0	1	1	1	1	1	0	0	1	1	1	1	1
VPN				Offset									

TLB		
Tag	PPN	Valid
0	1	1
2	3	1
1	2	1
3	4	1

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# offset bits =  $\log_2(\text{page size})$   
=  $\log_2(1024)$   
= 10

TLB hits	3
Page Faults	3

Page Table		
	Valid	PPN
0	1	1
1	1	2
2	1	3
3	1	4
4	0	5
5	1	6
6	1	7
7	0	NULL

Virtual Address												
0x	3			9				2				
0b	0	0	0	1	1	1	0	0	1	0	0	1
VPN			Offset									

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0	1	1
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# offset bits =  $\log_2(\text{page size})$   
=  $\log_2(1024)$   
= 10

TLB hits	4
Page Faults	3

Page Table		
	Valid	PPN
0	1	1
1	1	2
2	1	3
3	1	4
4	0	5
5	1	6
6	1	7
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Virtual Address													
0x	3			9				2					
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# offset bits =  $\log_2(\text{page size})$   
=  $\log_2(1024)$   
= 10

TLB hits	4
Page Faults	3

Page Table		
	Valid	PPN
0	1	1
1	1	2
2	1	3
3	1	4
4	0	5
5	1	6
6	1	7
7	0	NULL

Virtual Address												
0x	3			4				1				
0b	0	0	0	1	1	0	1	0	0	0	0	1
VPN				Offset								

TLB		
Tag	PPN	Valid
0	1	1
2	3	1
1	2	1
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How many TLB hits and page faults are there? What are the contents of the TLB at the end of the sequence?

# offset bits =  $\log_2(\text{page size})$   
=  $\log_2(1024)$   
= 10

TLB hits	5
Page Faults	3

Page Table		
	Valid	PPN
0	1	1
1	1	2
2	1	3
3	1	4
4	0	5
5	1	6
6	1	7
7	0	NULL

Virtual Address												
0x	3			4				1				
0b	0	0	0	1	1	0	1	0	0	0	0	1
VPN				Offset								

TLB		
Tag	PPN	Valid
0	1	1
2	3	1
1	2	1
3	4	1

# AMAT Calculations

Assume you are building a memory scheme with single level page tables. Each main memory access takes 50 ns and each TLB access takes 10 ns.

1. Assuming no page faults (i.e. all virtual memory is resident,) what TLB hit rate is required for an AMAT of 61 ns?
2. Assuming a TLB hit rate of 50%, how does the AMAT of this scenario compare to no TLB?
3. To improve your system, you add a two level paging scheme and a cache. The cache has a 90% hit rate with a lookup time of 20 ns. Additionally, the TLB hit rate is now improved to 95%. What is the average time to read a location from memory?

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1. Assuming no page faults (i.e. all virtual memory is resident,) what TLB hit rate is required for an AMAT of 61 ns?

$$(10+50) \times \text{hit rate} + (1 - \text{hit rate}) \times (10 + 50 + 50) = 61.$$

Solving for hit rate gives 98%.

2. Assuming a TLB hit rate of 50%, how does the AMAT of this scenario compare to no TLB?

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Solving for hit rate gives 98%.

2. Assuming a TLB hit rate of 50%, how does the AMAT of this scenario compare to no TLB?

$$\text{With TLB: AMAT} = (10 + 50) \times 0.5 + (1 - 0.5) \times (10 + 50 + 50) = 85 \text{ ns}$$

$$\text{Without TLB: AMAT} = 50 + 50 = 100 \text{ ns}$$

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3. To improve your system, you add a two level paging scheme and a cache. The cache has a 90% hit rate with a lookup time of 20 ns. Additionally, the TLB hit rate is now improved to 95%. What is the average time to read a location from memory?

$$\text{AMAT} = 0.9 \times 20 + 0.1 \times (20 + 50) = 25 \text{ ns}$$

$$\text{Page table stored in memory} \rightarrow 25 \times 3 = 75 \text{ ns}$$

$$\text{Need to incorporate TLB cost as well} \rightarrow 0.95 \times (10 + 25) + 0.05 \times (10 + 75) = 37.5 \text{ ns}$$

# Associativity Analysis

A big data startup has just hired you to help design their new memory system for a byte-addressable system. Suppose the virtual and physical memory address space is 32 bits with a 4KB page size.

1. First, you create a direct mapped cache and a fully associative cache of the same size that uses an LRU replacement policy. You run a few tests and realize that the fully associative cache performs much worse than the direct mapped cache does. What's a possible access pattern that could cause this to happen?
2. Instead, your boss tells you to build a 8KB 2-way set associative cache with 64 byte cache blocks. How would you split a given virtual address into its tag, index, and offset numbers?

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Let's say each cache held  $X$  amount of blocks. An access pattern would be to repeatedly iterate over  $X + 1$  consecutive blocks, which would cause everything in the fully associative cache to miss every time.

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2. Instead, your boss tells you to build a 8KB 2-way set associative cache with 64 byte cache blocks. How would you split a given virtual address into its tag, index, and offset numbers?

$$\# \text{ offset bits} = \log_2 (\text{block size}) = 6$$

$$\# \text{ set bits} = \log_2 (\# \text{ sets}) = \log_2 ((\text{cache size} \div \text{associativity}) \div \# \text{ blocks}) = \log_2 (2^{13-1} \div 2^6) = 6$$

$$\# \text{ tag bits} = \# \text{ virtual address bits} - \# \text{ set bits} - \# \text{ offset bits} = 32 - 6 - 6 = 20$$

# Replacement Roulette

Assume your program has the following memory access pattern: A, B, C, D, A, B, D, C, B, A.

1. How many misses will you get with FIFO?
2. How many misses will you get with LRU?
3. How many misses will you get with MIN?

# Replacement Roulette

Assume your program has the following memory access pattern: A, B, C, D, A, B, D, C, B, A.

1. How many misses will you get with FIFO?

	A	B	C	D	A	B	D	C	B	A
1	A			D			+	C		
2		B			A					+
3			C			B			+	

2. How many misses will you get with LRU?

3. How many misses will you get with MIN?

# Replacement Roulette

Assume your program has the following memory access pattern: A, B, C, D, A, B, D, C, B, A.

1. How many misses will you get with FIFO?

	A	B	C	D	A	B	D	C	B	A
1	A			D			+	C		
2		B			A					+
3			C			B			+	

2. How many misses will you get with LRU?

	A	B	C	D	A	B	D	C	B	A
1	A			D			+			A
2		B			A			C		
3			C			B			+	

3. How many misses will you get with MIN?

# Replacement Roulette

Assume your program has the following memory access pattern: A, B, C, D, A, B, D, C, B, A.

1. How many misses will you get with FIFO?

	A	B	C	D	A	B	D	C	B	A
1	A			D			+	C		
2		B			A					+
3			C			B			+	

2. How many misses will you get with LRU?

	A	B	C	D	A	B	D	C	B	A
1	A			D			+			A
2		B			A			C		
3			C			B			+	

3. How many misses will you get with MIN?

	A	B	C	D	A	B	D	C	B	A
1	A				+					+
2		B				+			+	
3			C	D			+	C		

# Replacement Roulette

Assume your program has the following memory access pattern: A, B, C, D, A, B, D, C, B, A.

4. If we increase the cache size, are we always guaranteed to get better cache performance? Explain for FIFO, LRU, and MIN.

# Replacement Roulette

Assume your program has the following memory access pattern: A, B, C, D, A, B, D, C, B, A.

4. If we increase the cache size, are we always guaranteed to get better cache performance? Explain for FIFO, LRU, and MIN.

FIFO suffers from Belady's anomaly, so there isn't a guarantee.

LRU and MIN are stack algorithms → contents of a cache with size  $S$  is always a subset of the contents of a cache with size  $S + 1$ .

# On the Clock

1. Suppose that we have a 10-10-12 virtual address split using a two-level paging scheme. Assume that the physical address is 32-bit as well and PTE is 4 bytes. Show the format of a page table entry (PTE) complete with bits required to support the clock algorithm.

# On the Clock

1. Suppose that we have a 10-10-12 virtual address split using a two-level paging scheme. Assume that the physical address is 32-bit as well and PTE is 4 bytes. Show the format of a page table entry (PTE) complete with bits required to support the clock algorithm.

# physical page number bits = # physical address bits - # offset bits

$$= 32 - 12$$

$$= 20$$

Have 12 bits remaining for clock algorithm, need dirty, use, writable, and valid bits.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

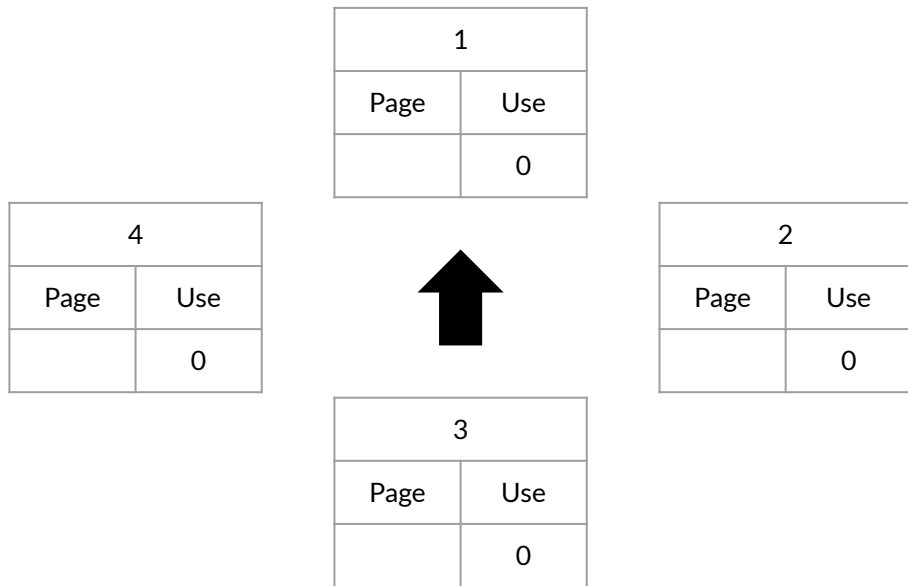
What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

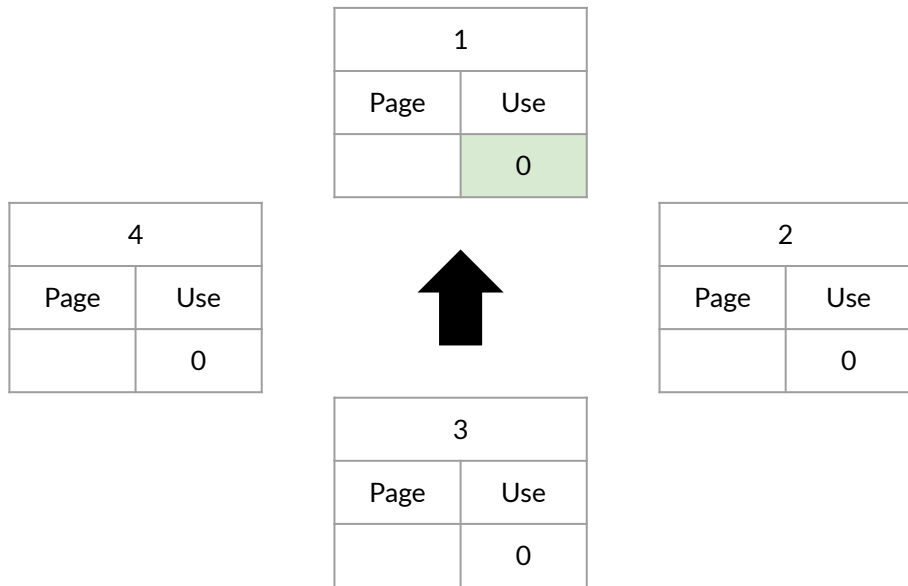
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. Advance clock hand.
3. Repeat if necessary.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

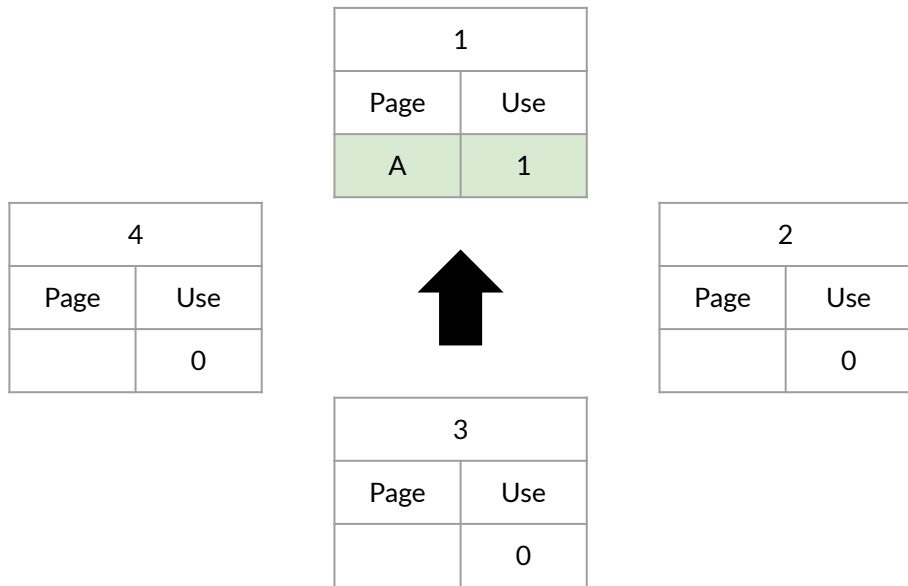
1. **Check use bit.**  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
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A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

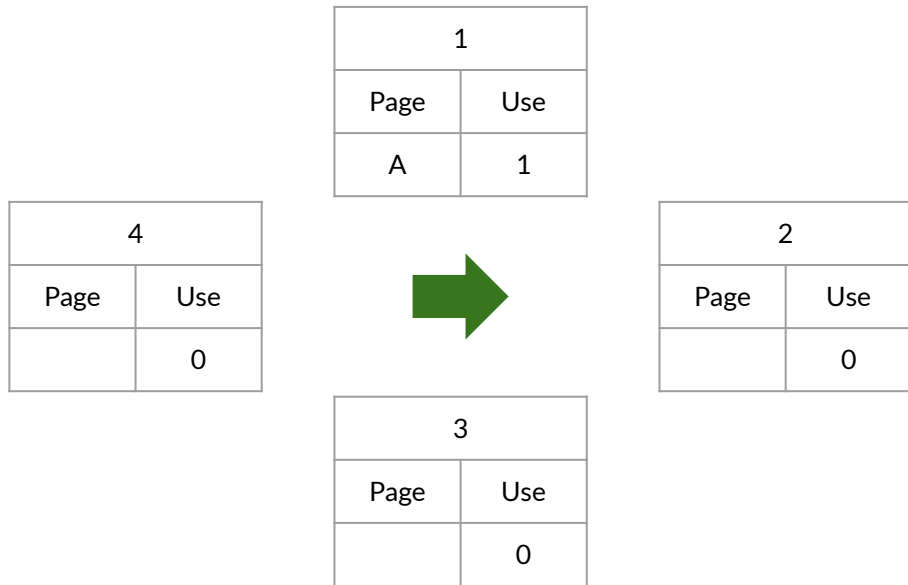
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. Advance clock hand.
3. Repeat if necessary.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

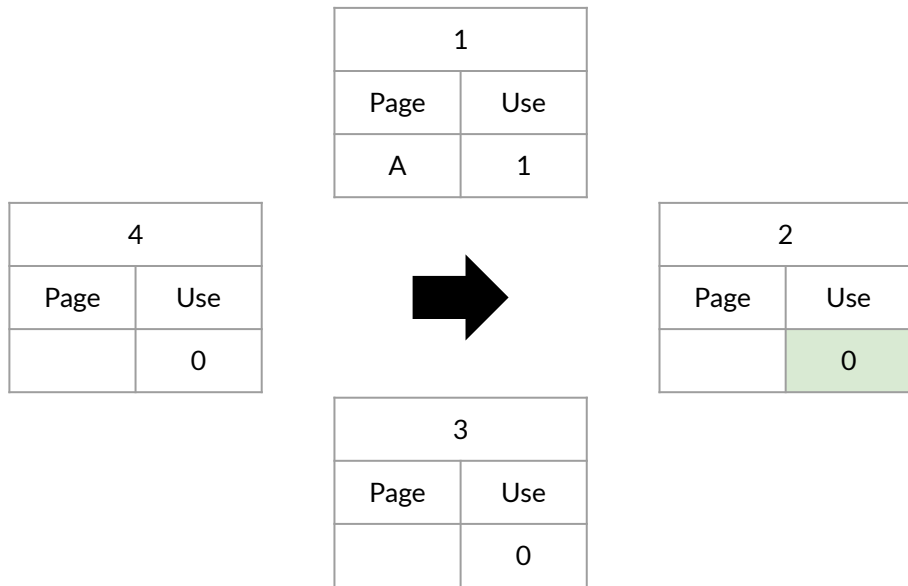
1. Check use bit.  
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1 → set use bit = 0.
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# On the Clock

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A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

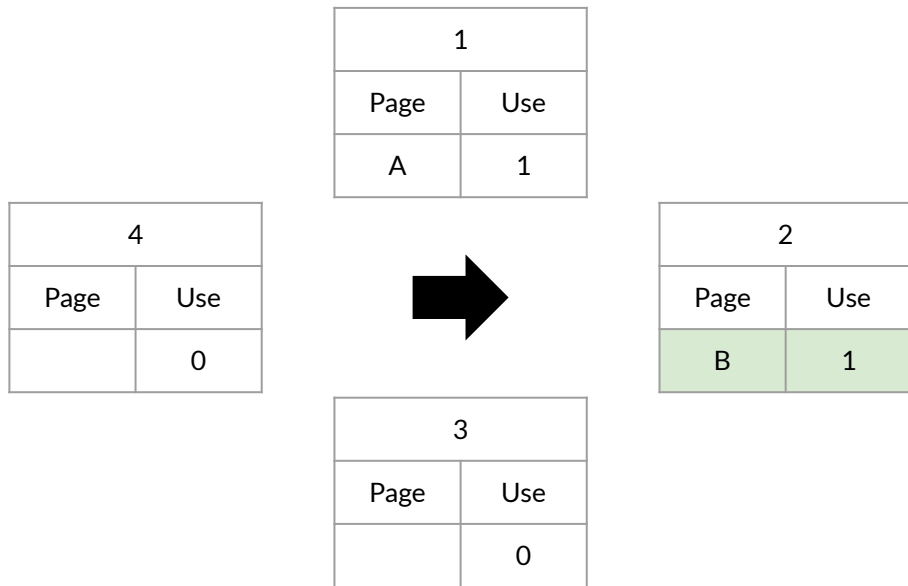
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
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# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

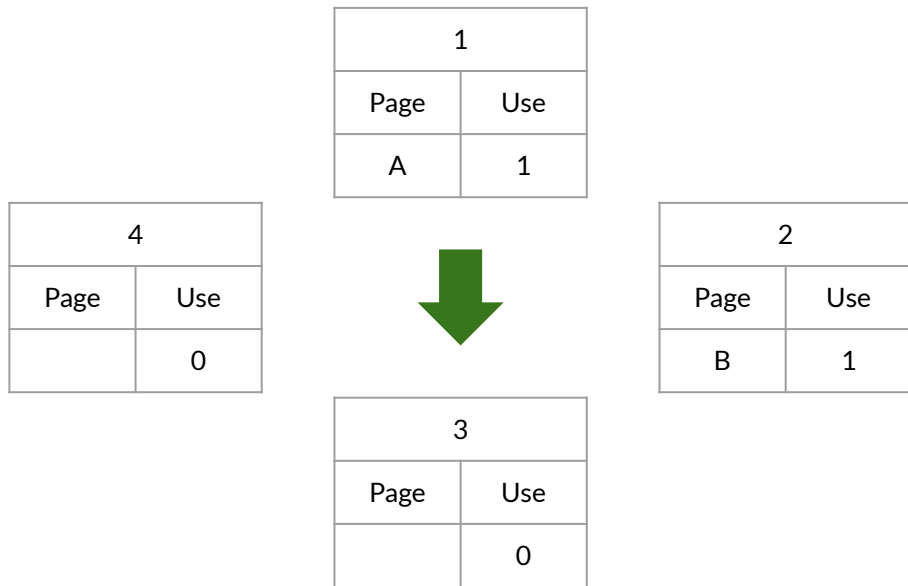
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. Advance clock hand.
3. Repeat if necessary.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

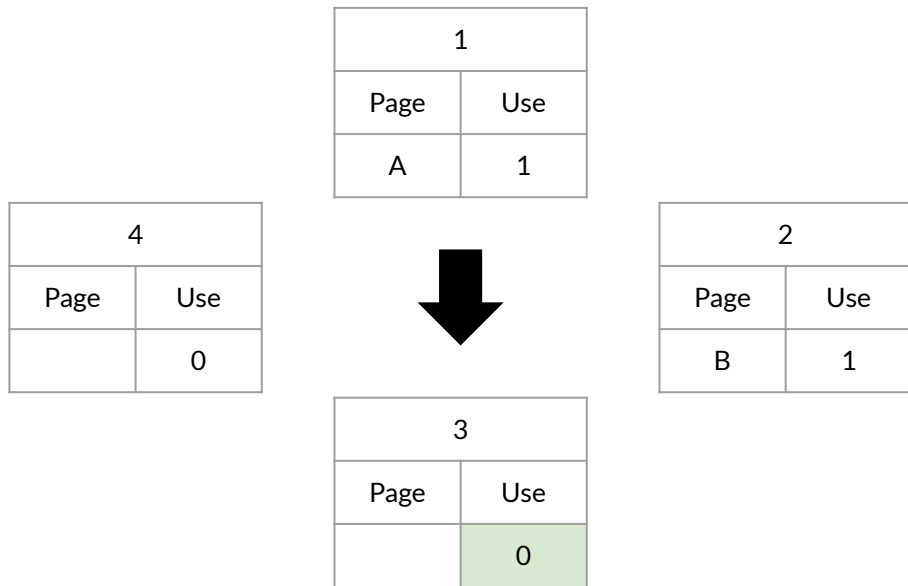
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. **Advance clock hand.**
3. Repeat if necessary.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

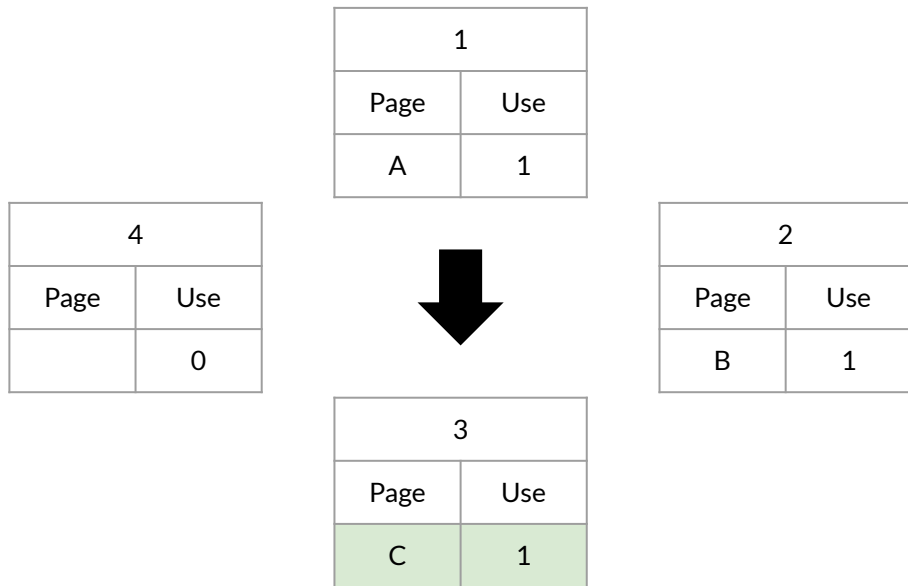
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. Advance clock hand.
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# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

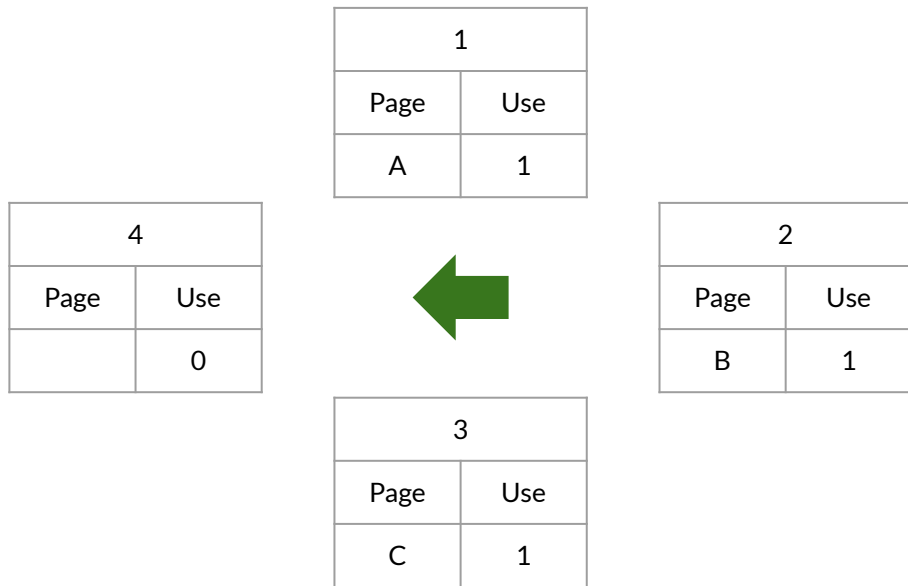
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. Advance clock hand.
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2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

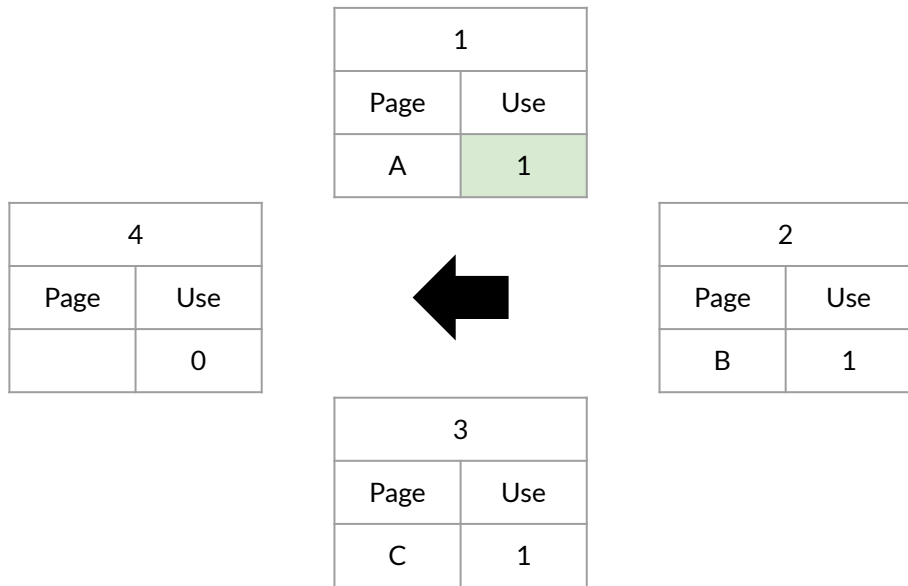
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
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2. **Advance clock hand.**
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2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



## Hit

1. Set use bit = 1 (don't advance clock hand).

## Miss

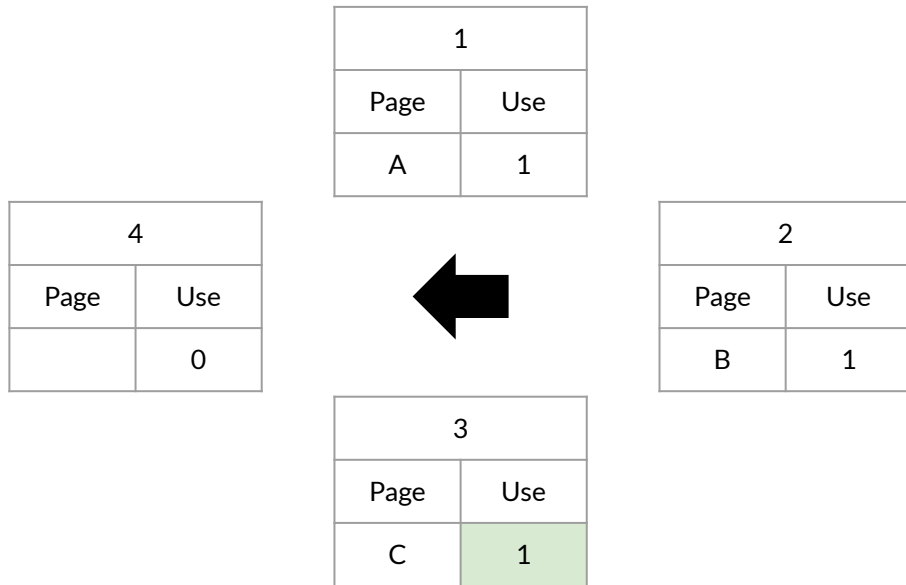
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2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



## Hit

1. Set use bit = 1 (don't advance clock hand).

## Miss

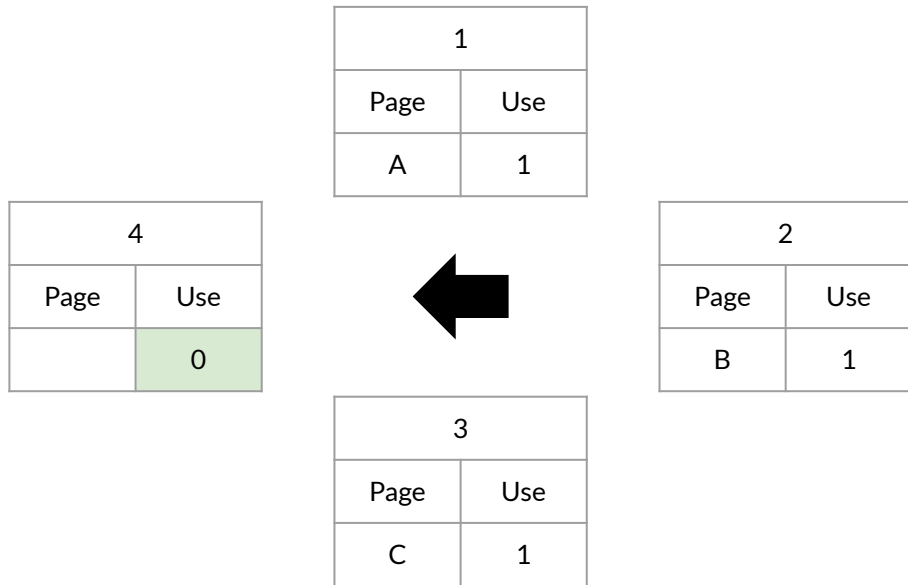
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. Advance clock hand.
3. Repeat if necessary.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, **D**, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

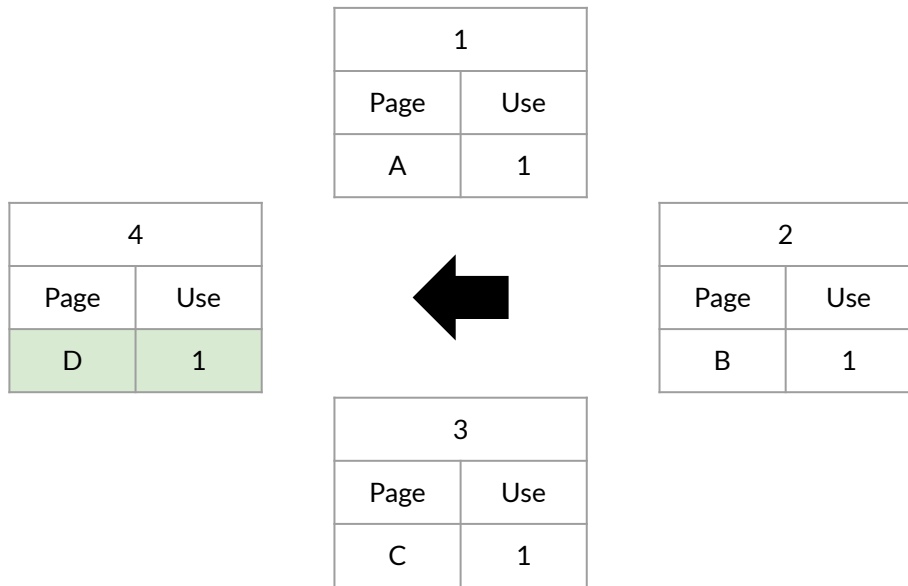
1. **Check use bit.**  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. Advance clock hand.
3. Repeat if necessary.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, **D**, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

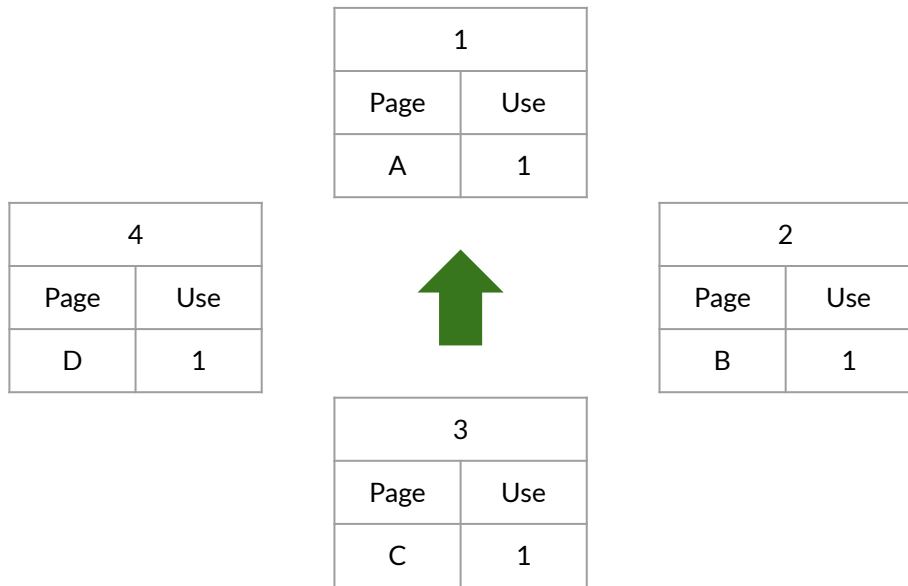
1. Check use bit.  
**0 → evict entry (if necessary), bring in page, set use bit = 1.**  
**1 → set use bit = 0.**
2. Advance clock hand.
3. Repeat if necessary.

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A, B, C, A, C, **D**, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

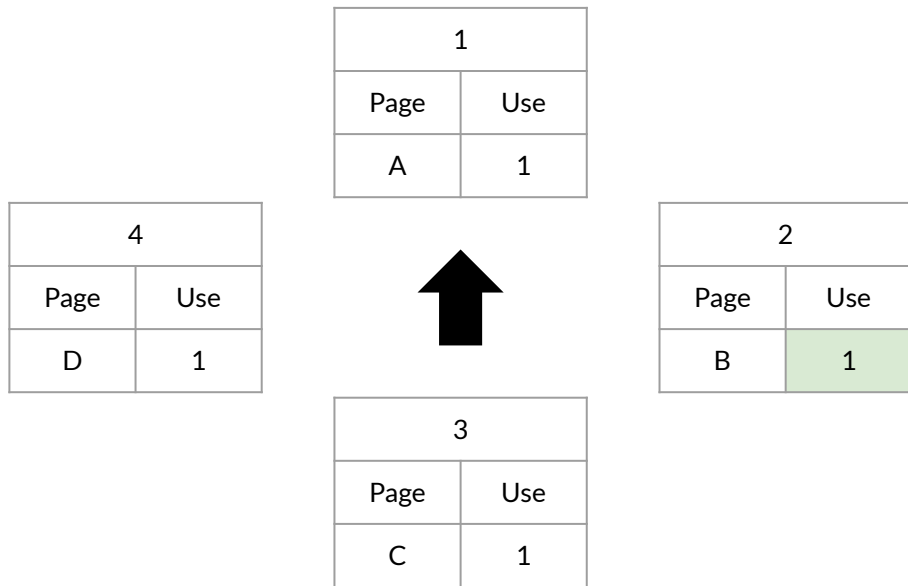
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. **Advance clock hand.**
3. Repeat if necessary.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, **B**, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



## Hit

1. Set use bit = 1 (don't advance clock hand).

## Miss

1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. Advance clock hand.
3. Repeat if necessary.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, **D**, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?

4	
Page	Use
D	1

1	
Page	Use
A	1



3	
Page	Use
C	1

2	
Page	Use
B	1

## Hit

1. Set use bit = 1 (don't advance clock hand).

## Miss

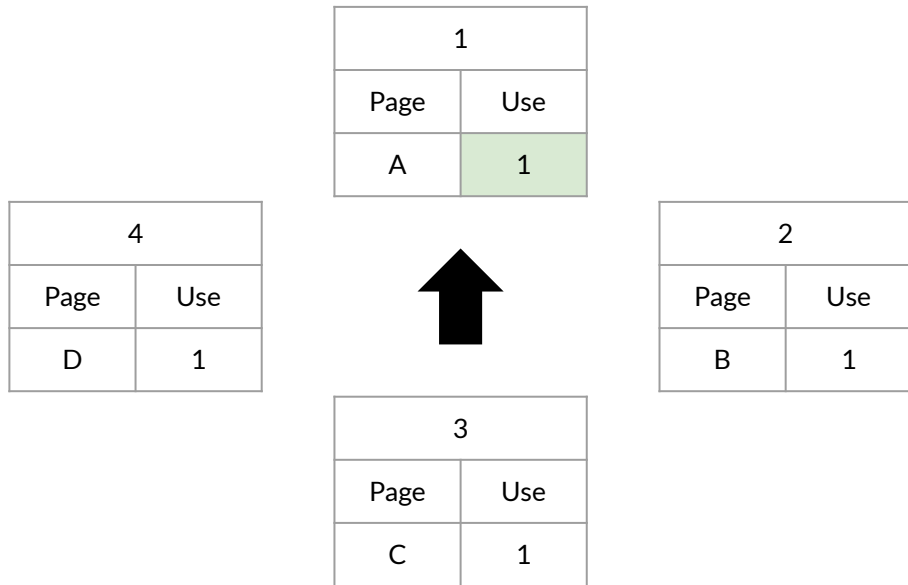
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. Advance clock hand.
3. Repeat if necessary.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, **A**, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



## Hit

1. Set use bit = 1 (don't advance clock hand).

## Miss

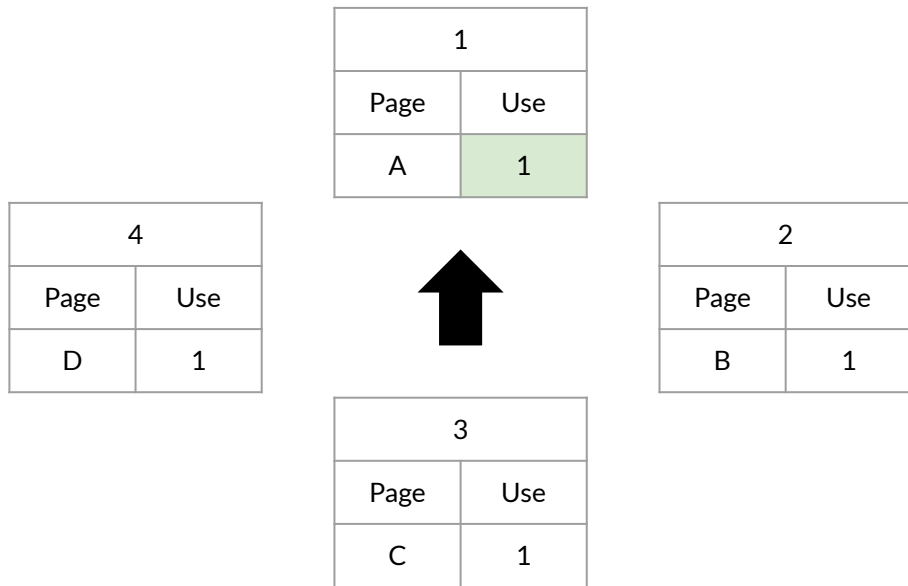
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
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3. Repeat if necessary.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, **E**, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

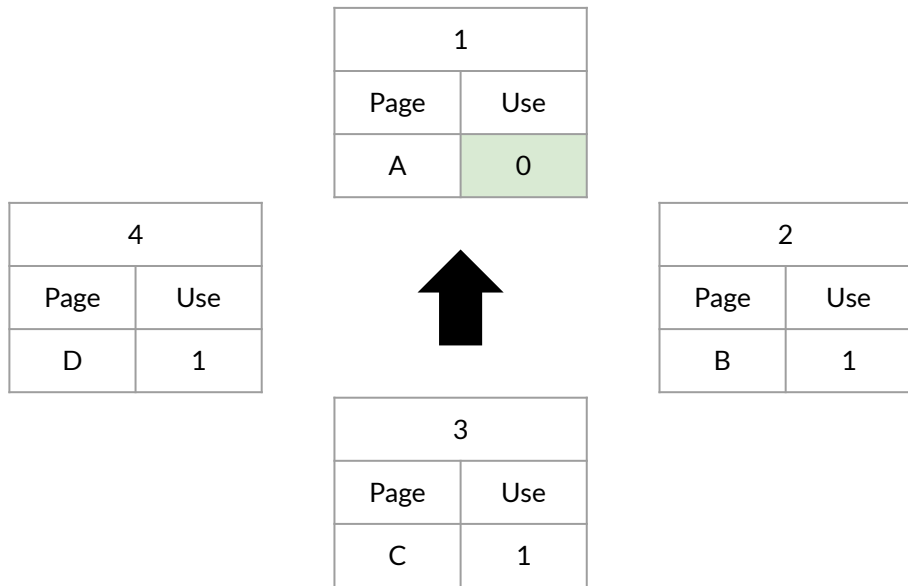
1. **Check use bit.**  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
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A, B, C, A, C, D, B, D, A, **E**, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

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Miss

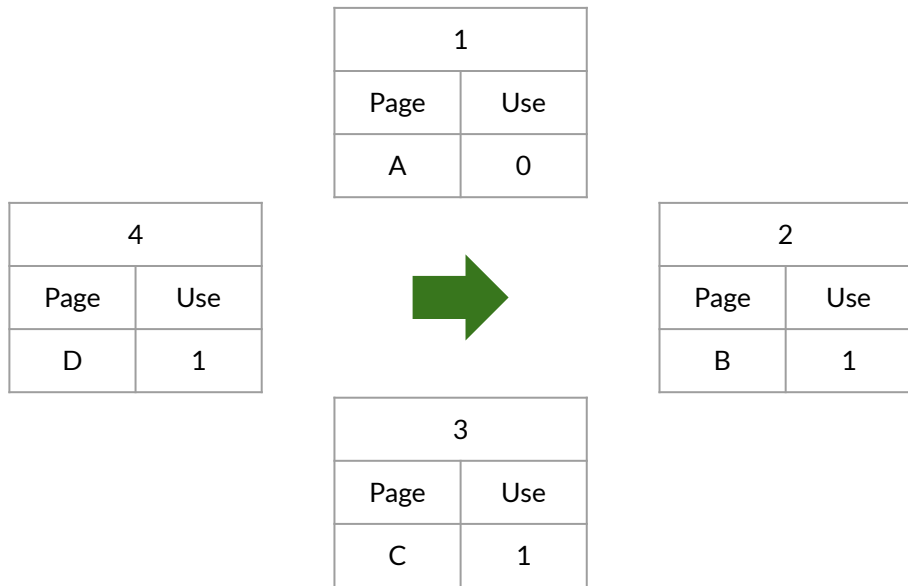
1. **Check use bit.**  
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# On the Clock

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A, B, C, A, C, D, B, D, A, **E**, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

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Miss

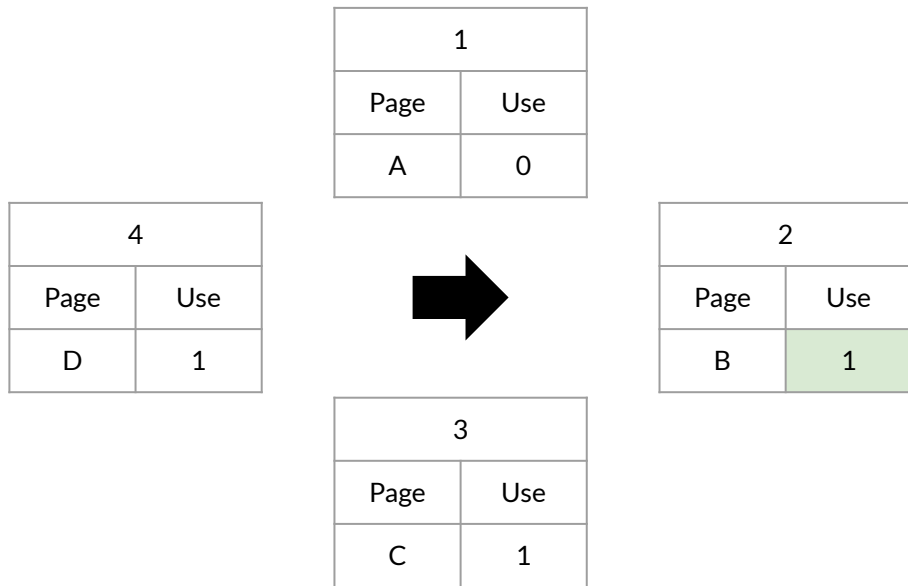
1. Check use bit.  
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1 → set use bit = 0.
2. **Advance clock hand.**
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# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, **E**, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

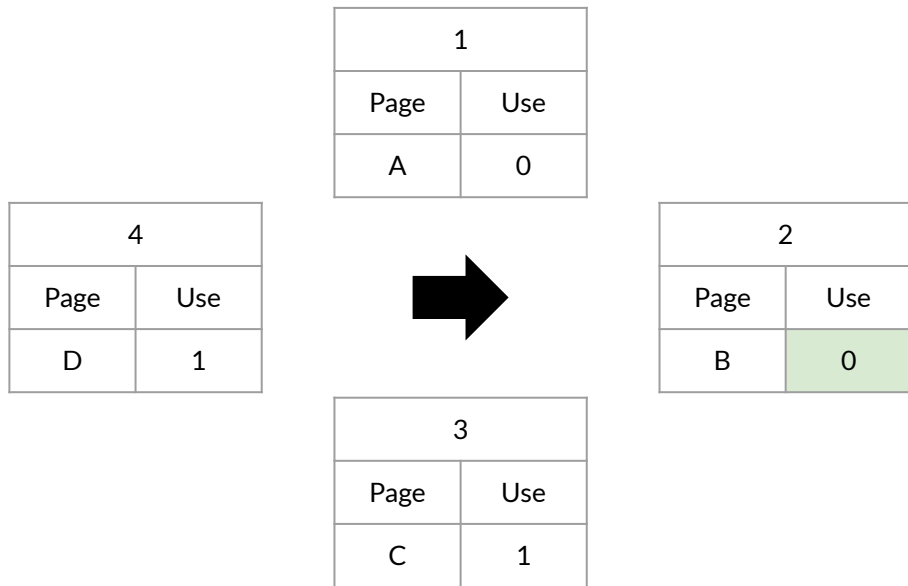
1. **Check use bit.**  
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A, B, C, A, C, D, B, D, A, **E**, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

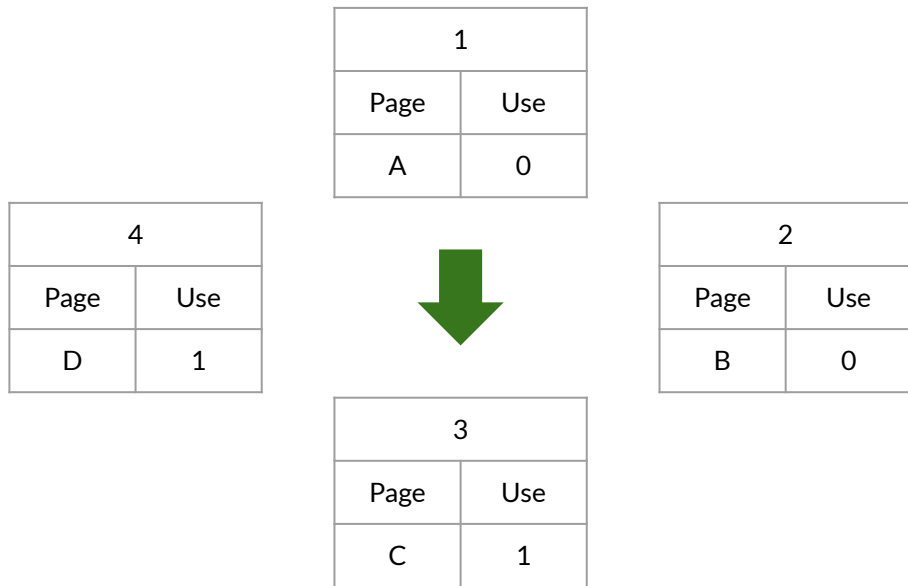
1. **Check use bit.**  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
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# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, **E**, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

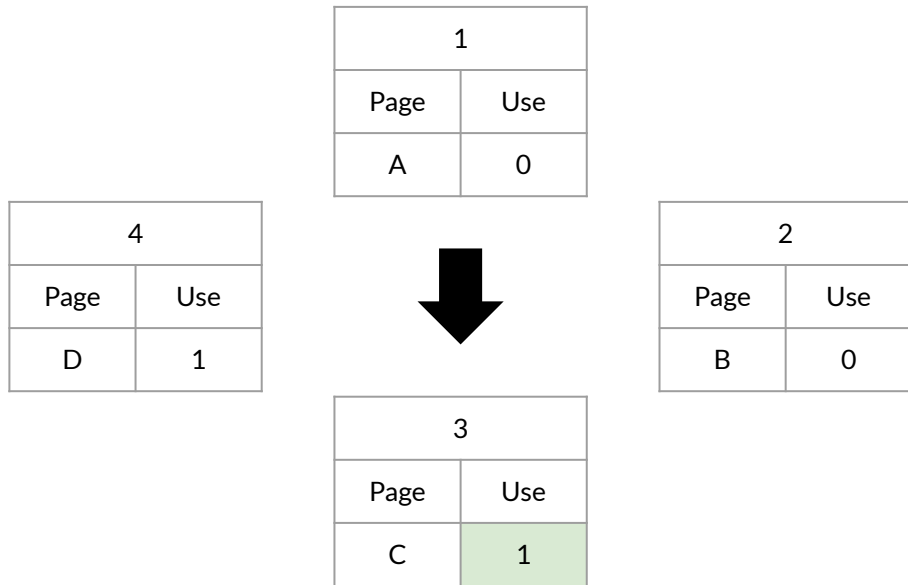
1. Check use bit.  
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# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, **E**, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

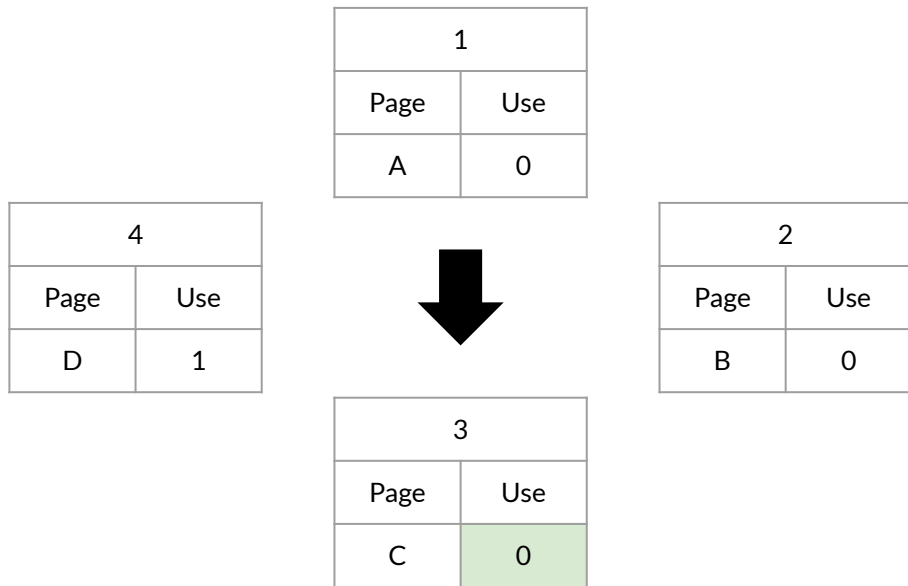
1. **Check use bit.**  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. Advance clock hand.
3. Repeat if necessary.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

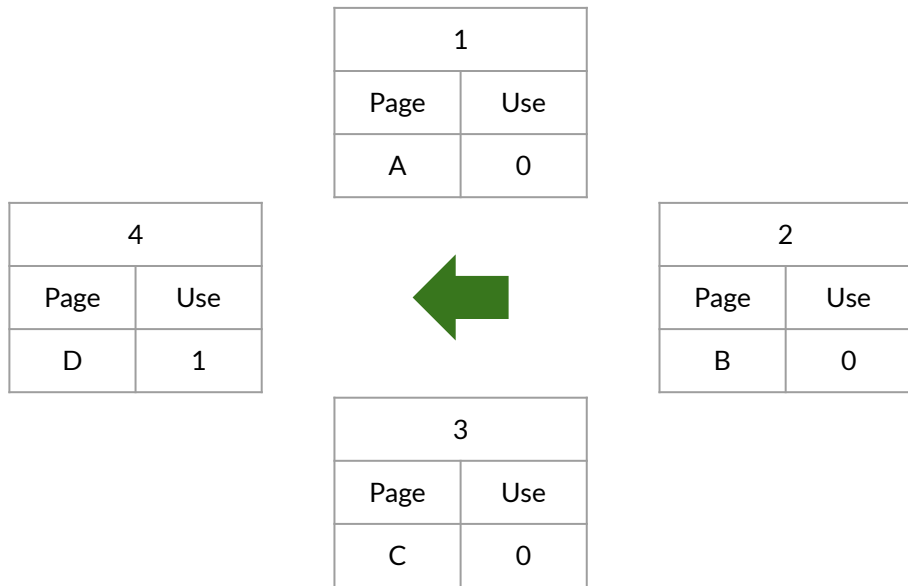
1. Check use bit.  
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1 → set use bit = 0.
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# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, **E**, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

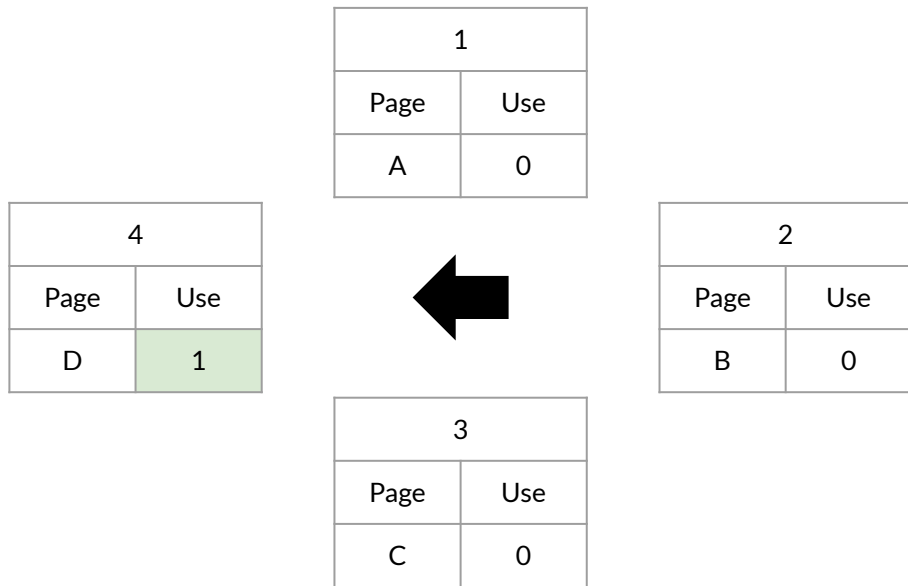
1. Check use bit.  
0 → evict entry (if necessary), bring in page, set use bit = 1.  
1 → set use bit = 0.
2. **Advance clock hand.**
3. Repeat if necessary.

# On the Clock

2. Assume that physical memory can hold at most four pages. The program you run has the following memory access pattern

A, B, C, A, C, D, B, D, A, E, B, F

What pages remain in memory at the end of the following sequence of page table operations? What are the use bits set to for each of these pages?



Hit

1. Set use bit = 1 (don't advance clock hand).

Miss

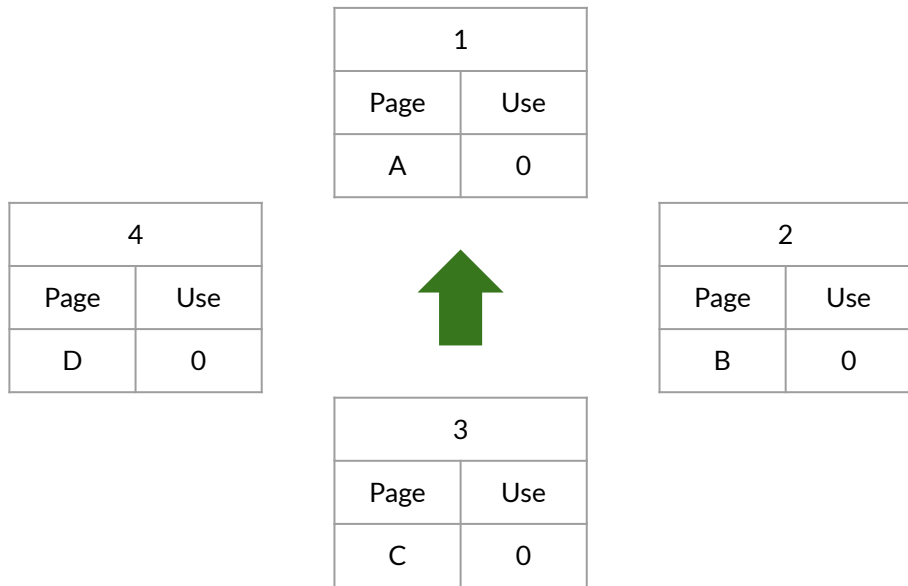
1. **Check use bit.**  
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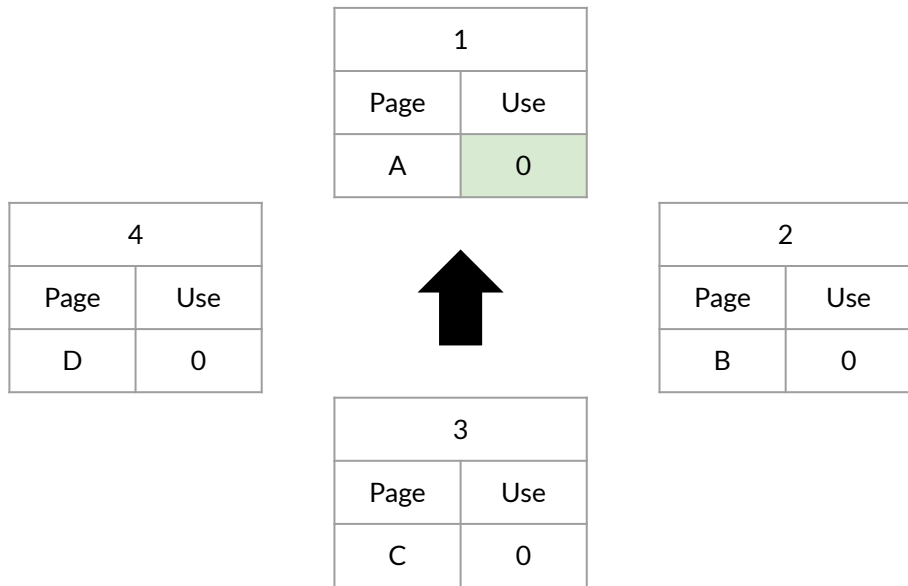
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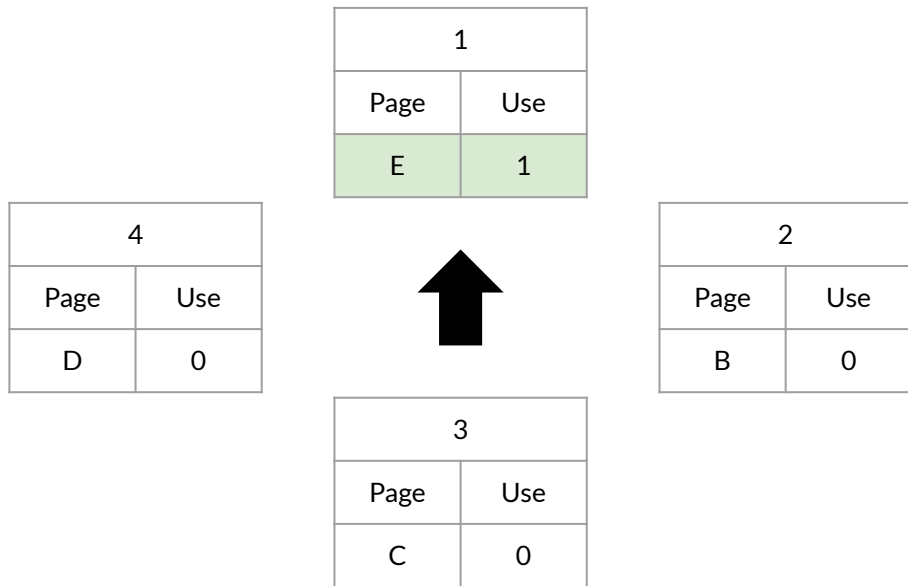
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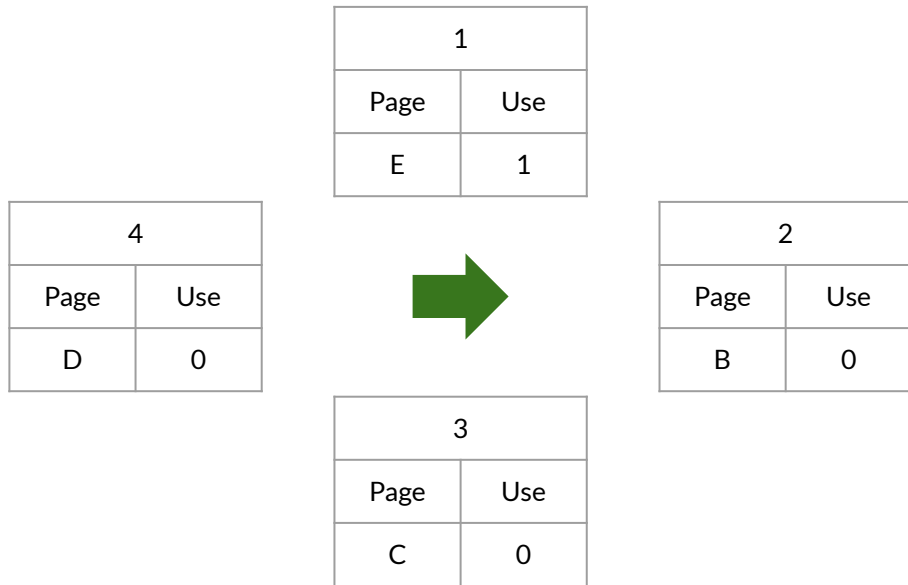
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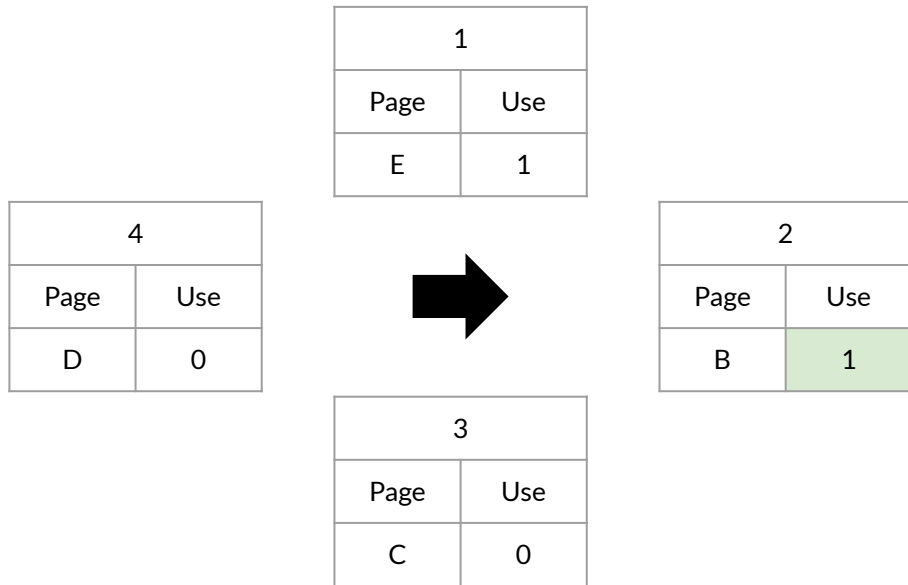
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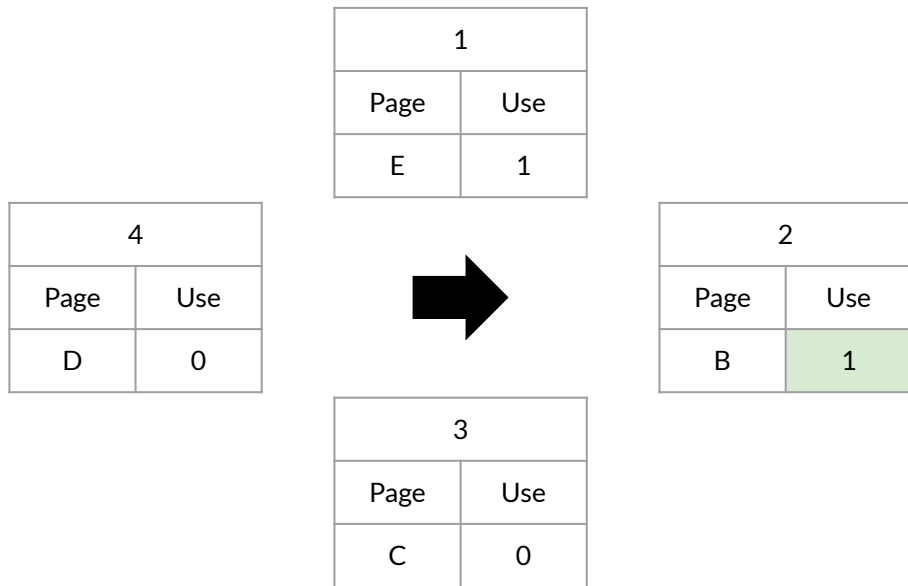
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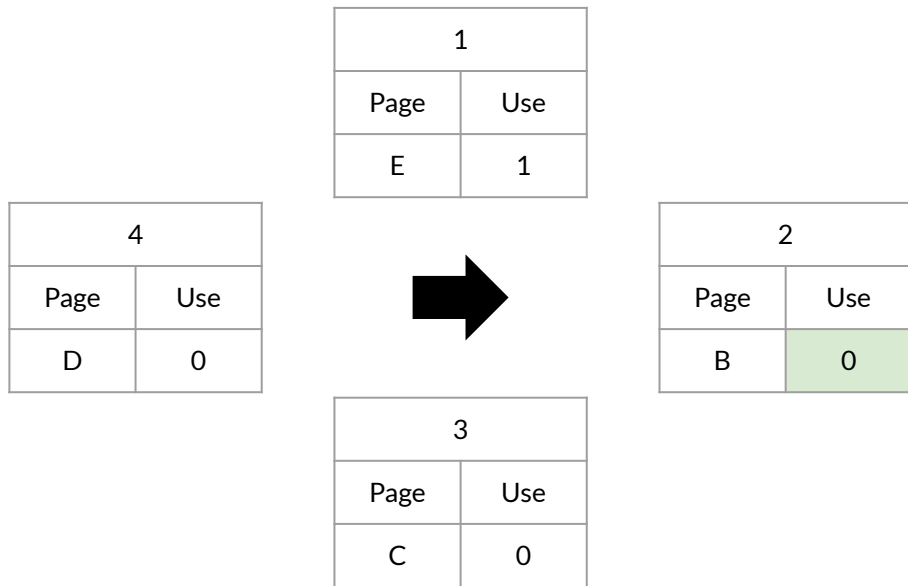
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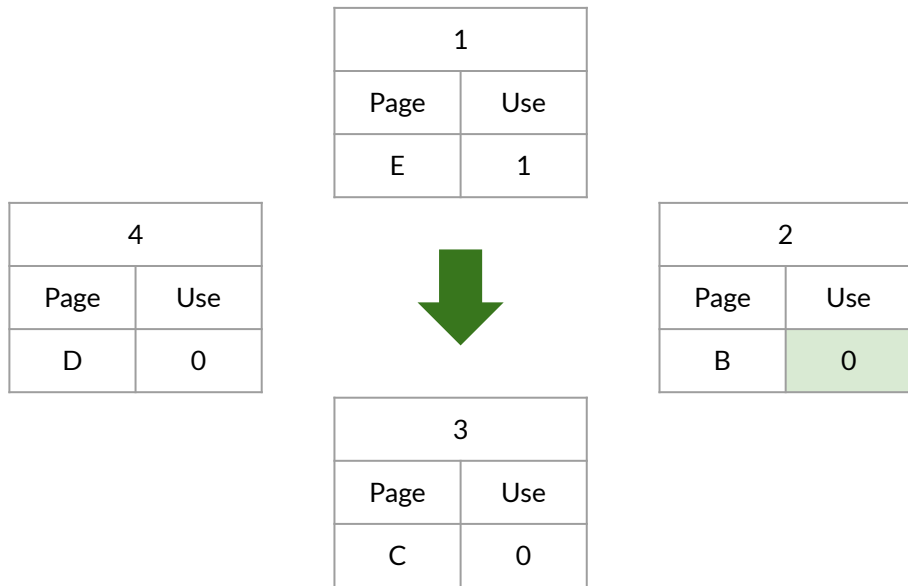
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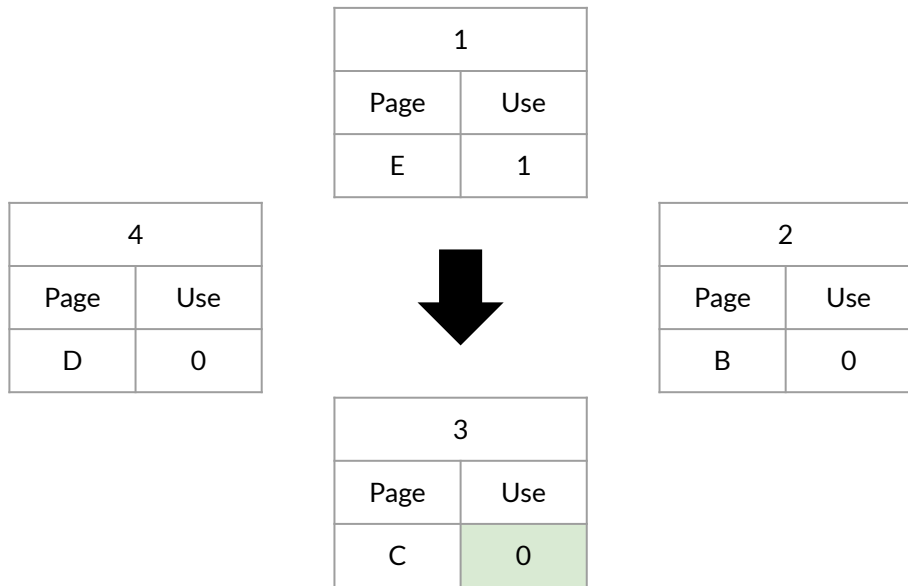
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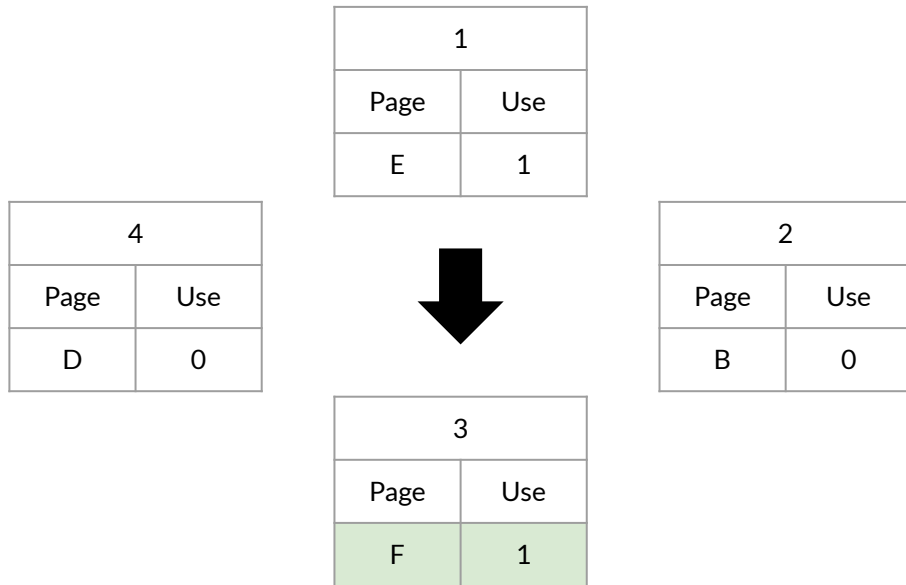
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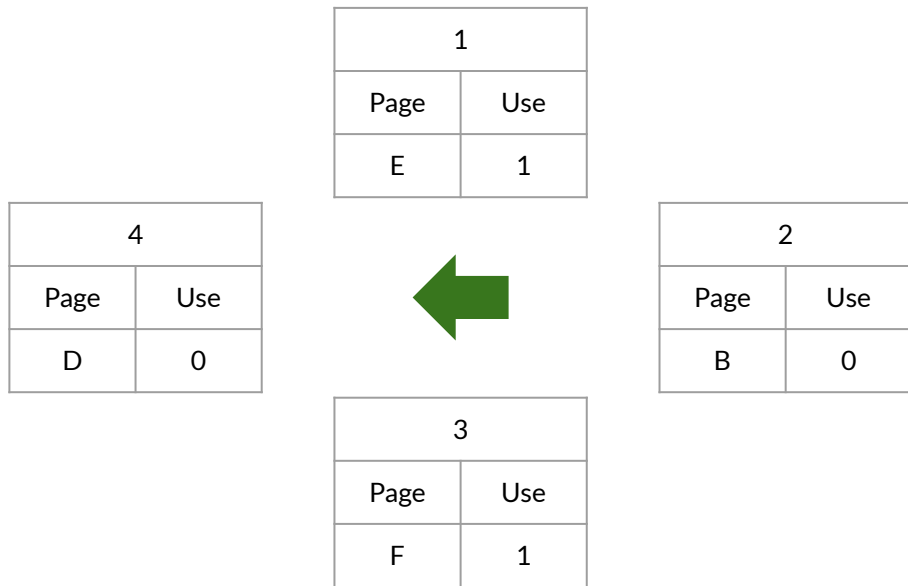
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