Quincy Flint

Virtual Memory

EEL 3713C: Digital Computer Architecture

Quincy Flint

[Ionospheric Radio Lab in NEB]

Outline

Quincy Flint

1. Memory Problems

- Not enough memory
- Holes in address space
- Programs overwriting

2. What is Virtual Memory?

- Layer of indirection
- How does indirection solve above
- Page tables and translation

3. How do we implement VM?

- Create and store page tables
- Fast address translation

4. Virtual Memory and Caches

 Prevent cache performance degradation when using VM

Quincy Flint

TLB Example

Computer Signal Computer Signa

32-bit Virtual Address28-bit Physical Address

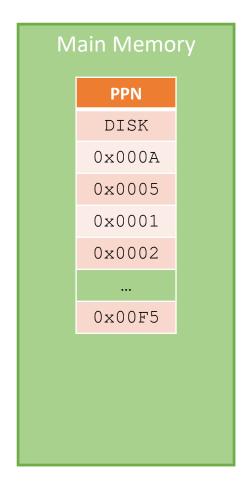
12-bit Page Offset [Index]

Virtual Address [32 bit]

Virtual Page 20 bits	Page 12 bits
Number 20 DitS	Offset 12 DILS

TLB [2-entries big]		
Tag	Physical Page #	

Physical Page Number 16 bits Page Offset	12 bits
--	---------



Computers be 5:
32 pit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address28-bit Physical Address

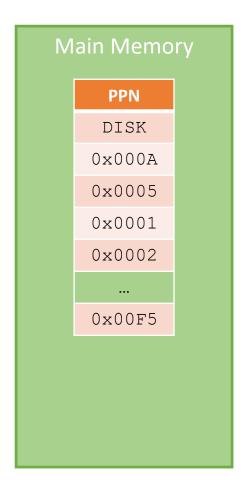
12-bit Page Offset [Index]

Virtual Address [32 bit]

	Virtual Page Number		Page Offset	
3	31	12	11	0

TLB [2-entries big]		
Tag	Physical Page #	

Physical Page Number	Page Offset	
27	12 11	0



Comut rispes:
32 pit iA, .56 / IB f RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

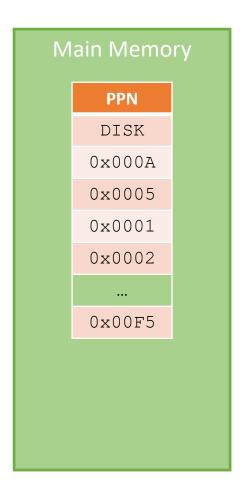
Virtual Address [32 bit]

Virtual Page Number	Page Offset	
31 12	11 ()

TLB [2-entries big] Tag Physical Page # 0x0 0001 0x000A

1 entry already filled

Physical Page Number	Page Offset	
27	12 11	0



TLB Exampled UINCY

C(m ut r \)e ;: 32 pit SA, 56 / 1B * RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

32-bit Virtual Address 28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]

Virtua Numb	_	Page Offset	
31		12 11	0

Tag Physical Page #	TLB [2-entries big]			
0x0 0001 0x000A				

Physical Address [28 bits]

Physical Page Number	Page Offset	
27	12 11	0

Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

Computers be 5:
32 pit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00003 <u>103</u>

32-bit Virtual Address28-bit Physical Address

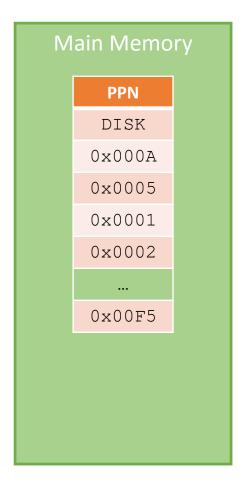
12-bit Page Offset [Index]

Virtual Address [32 bit]

	Virtual Page Number		Page Offset	
-	31	12	11	0

Tag Physical Page	TLB [2-entries big]			
Tag Physical Page #				
0x0 0001 0x000A				

Physical Page Number	Page Offset	
27	12 11	0



Computers be 5:
32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

32-bit Virtual Address28-bit Physical Address

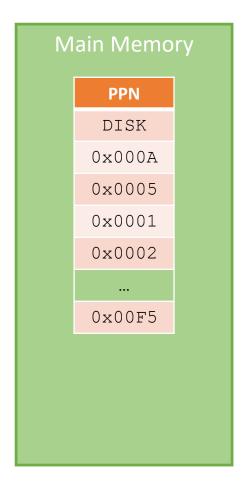
12-bit Page Offset [Index]

Virtual Address [32 bit]

	/irtual Page Number	Page Offset	103	
3:	l	11		0

TLB [2-entries big]			
Tag	Physical Page #		
0x0 0001	0×000A		

Physical Page Number	Page Offset	
27	12 11	0

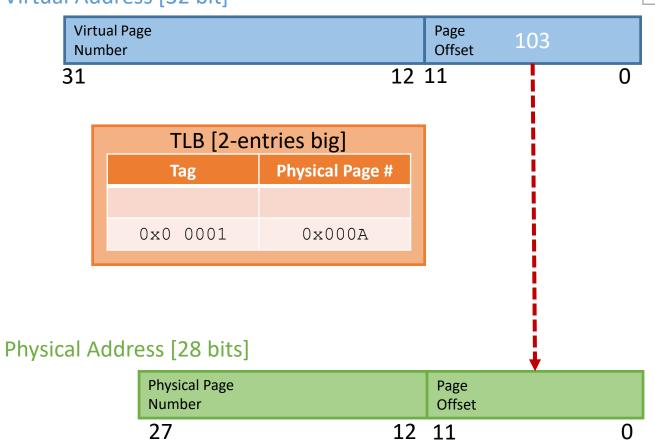


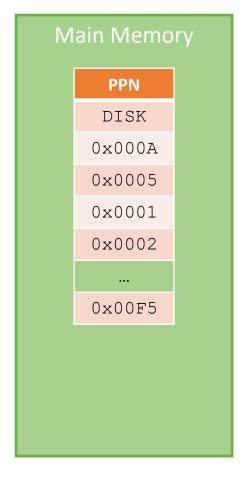
Computers be 5: 32 bit 5A, 56 4B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



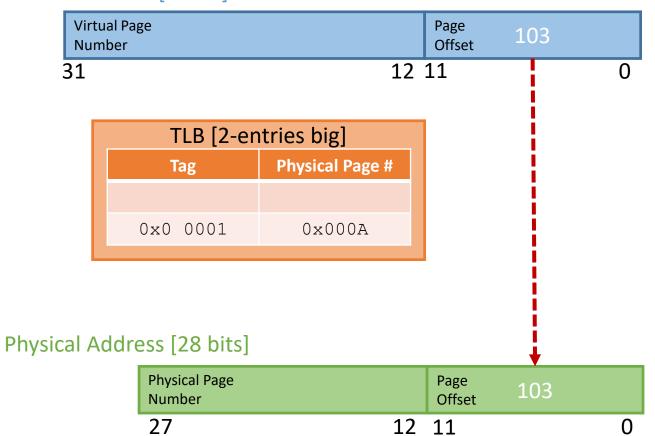


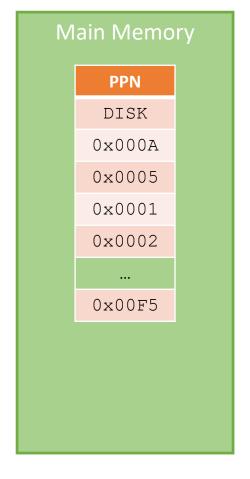
Computers be 5: 32 pit 5A, 56 4B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



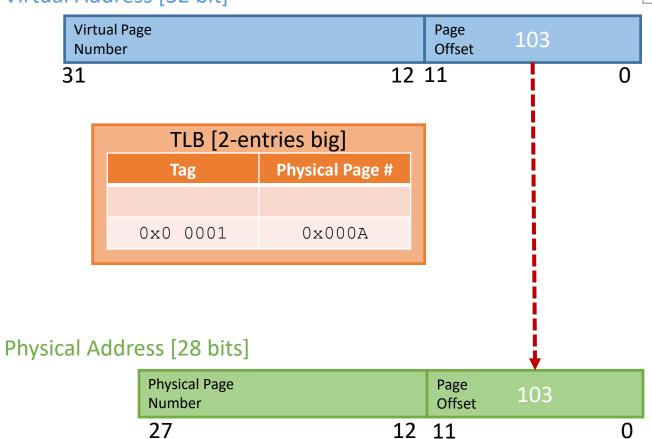


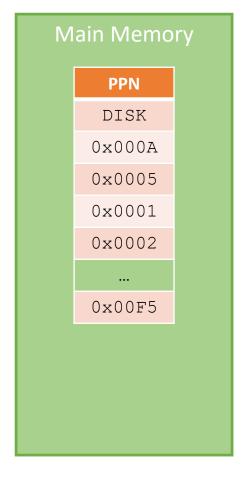
Computers be 5: 32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x<u>00003</u> 103

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



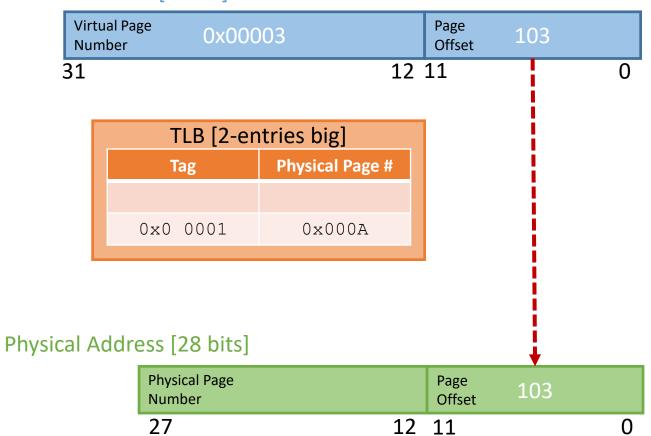


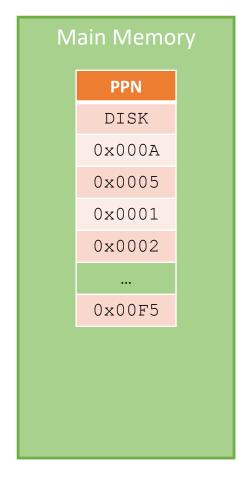
Computers be 3: 32 bit 3A, 56 / B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



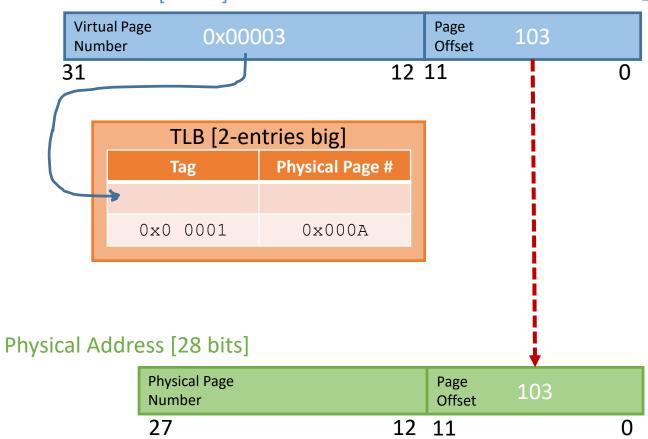


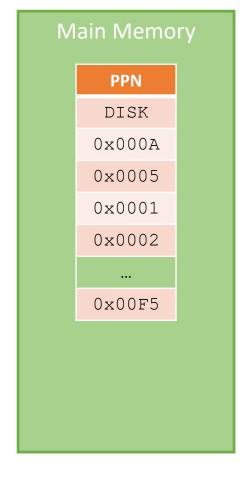
Computers be 5: 32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x<u>00003</u> 103

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]





Computers be s:

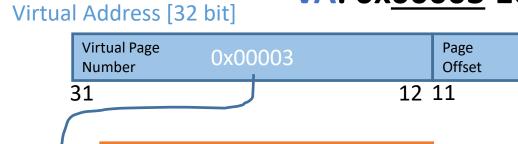
32 pit sA, 56 /B FRAM, 4 kB pages, 2-entry TLB

VA: 0x<u>00003</u> 103

103

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



TLB [2-entries big]

Tag Physical Page #

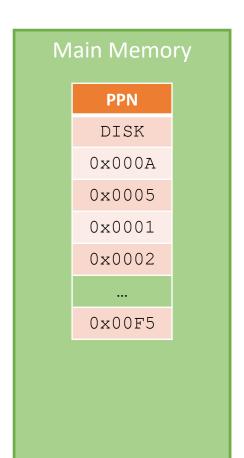
0x0 0001 0x000A

Physical Address [28 bits]

Physical Page Number Page Offset 103

27 12 11 0

Compulsory Miss!



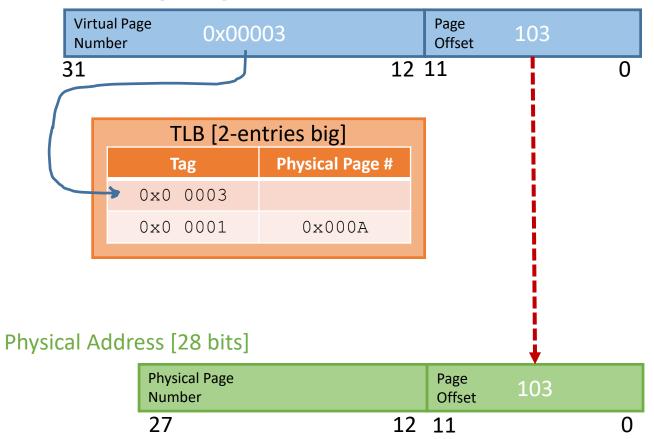
Computers be 5:
32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x<u>00003</u> 103

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]



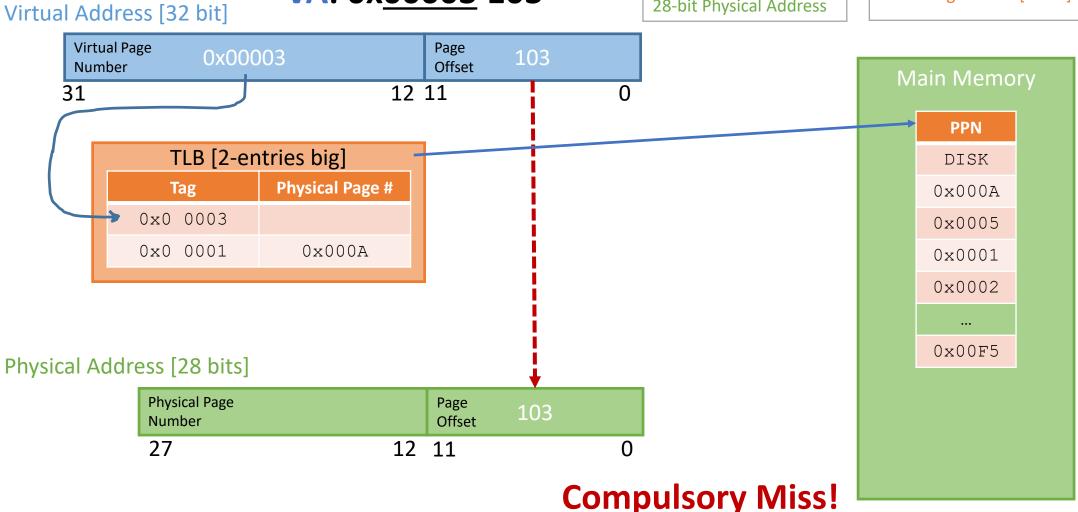
Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

Compulsory Miss!

Computers be 5:
32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x<u>00003</u> 103

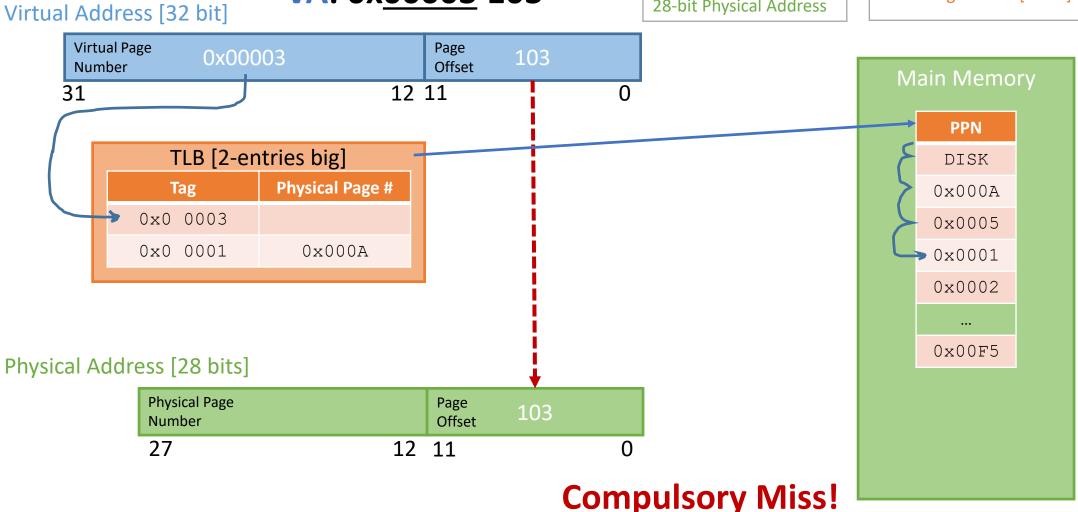
32-bit Virtual Address28-bit Physical Address



Computers be 5: 32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

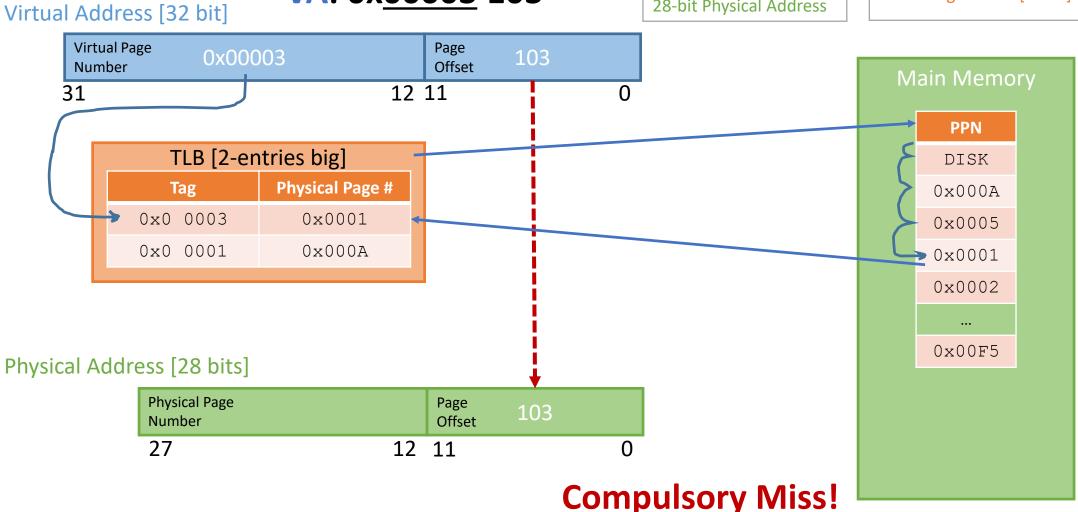
32-bit Virtual Address28-bit Physical Address



Computers be 5: 32 bit 5A, 56 4B * RAM, 4 kB pages, 2-entry TLB

VA: 0x<u>00003</u> 103

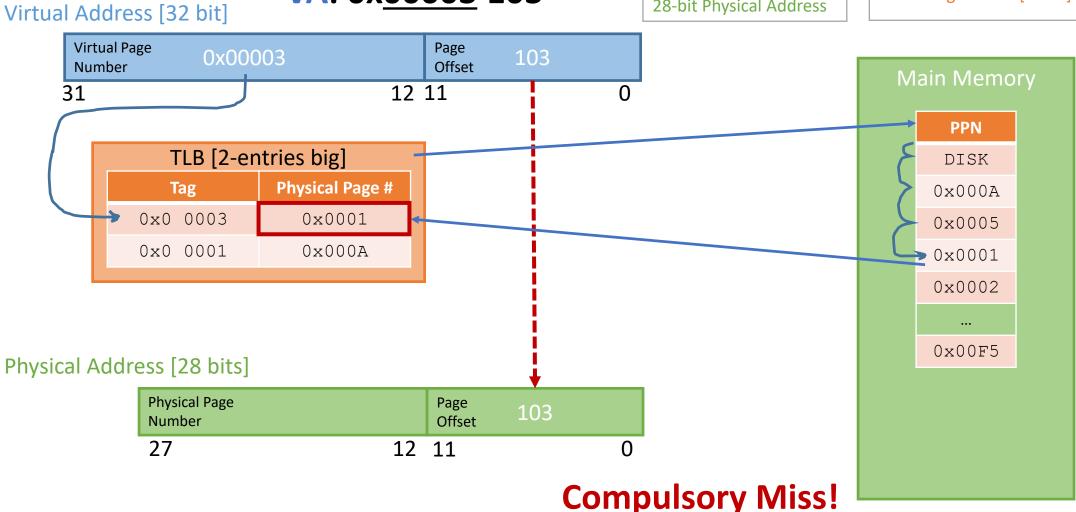
32-bit Virtual Address28-bit Physical Address



Computers be 5: 32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x<u>00003</u> 103

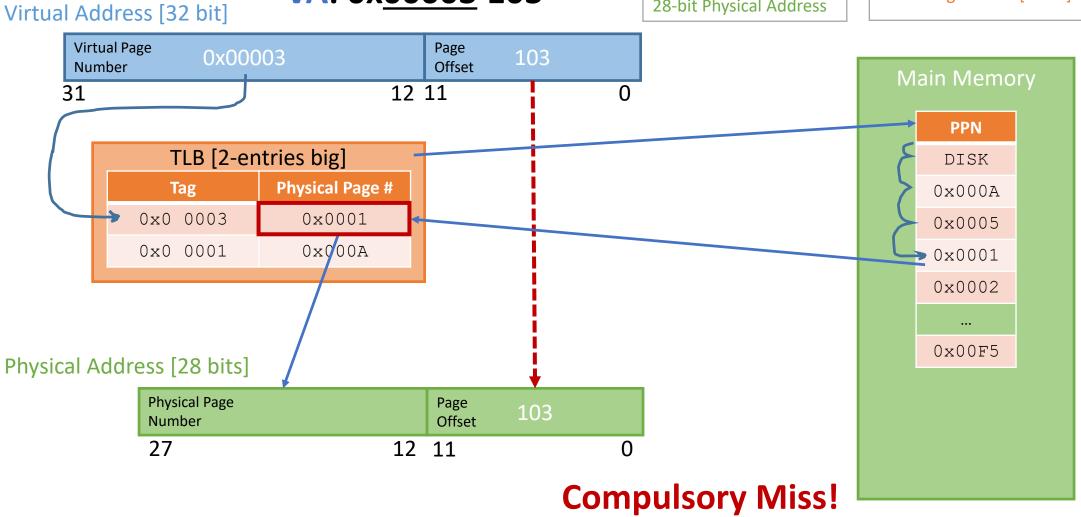
32-bit Virtual Address28-bit Physical Address



Computers be 5:
32 pit 5A, 56 /B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

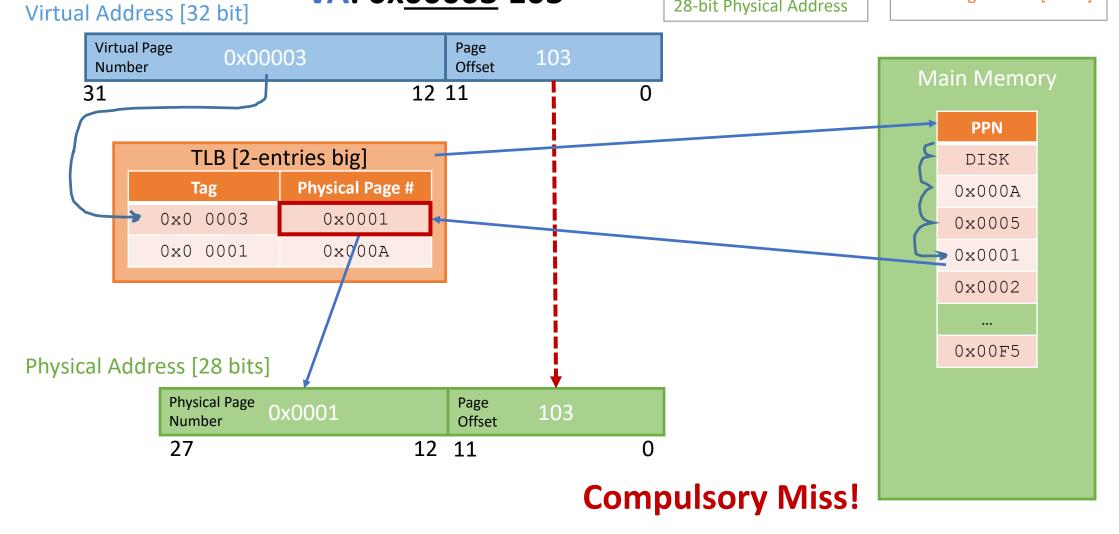
32-bit Virtual Address28-bit Physical Address



Computers be 5: 32 bit 5A, 56 4B f RAM, 4 kB pages, 2-entry TLB

VA: 0x<u>00003</u> 103

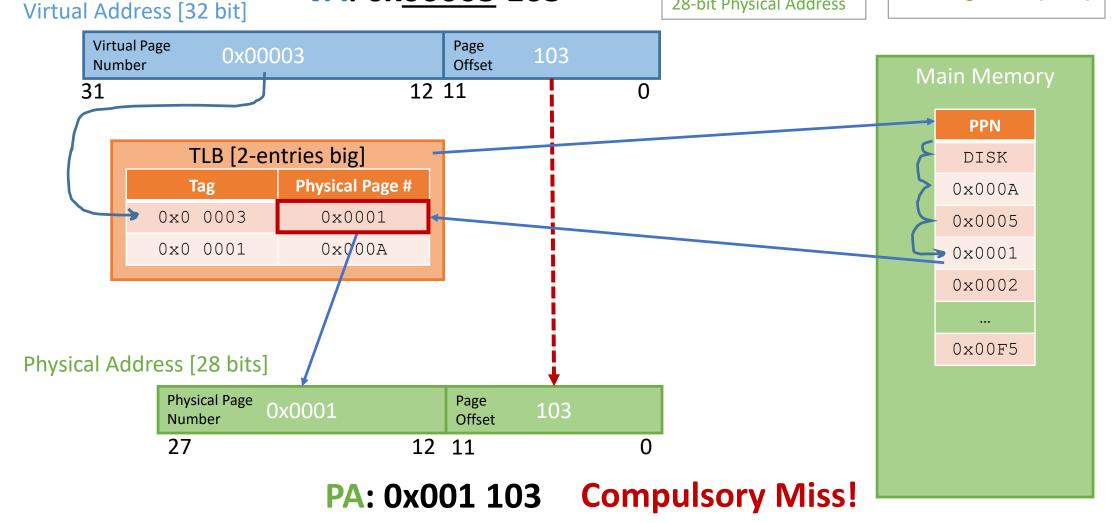
32-bit Virtual Address28-bit Physical Address



Computers be 5:
32 pit 5A, 56 /B FRAM, 4 kB pages, 2-entry TLB

VA: 0x<u>00003</u> 103

32-bit Virtual Address28-bit Physical Address



Computers be 5:
32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Main Memory

Virtual Address [32 bit]

	Virtual Page Number		Page Offset	
-	31	12	11	0

TLB [2-entries big]		
T	ag	Physical Page #
0x0	0003	0x0001
0x0	0001	A000x0

PPN
DISK
0x000A
0x0005
0x0001
0x0002
...
0x00F5

Physical Page Number	Page Offset	
27	12 11	0

Computers be 5:
32 pit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]

	/irtual Page Number		Page Offset	
31	1	12	11	0

Tag Physical Page # 0x0 0003 0x0001 0x0 0001 0x0002	TLB [2-entries big]			
	Tag	Physical Page #		
0~0 0001 0~000	0x0 0003	0x0001		
0X0 0001 0X000A	0x0 0001	A000x0		

Physical Address [28 bits]

Physical Page Number	Page Offset	
27	12 11	0

Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

Computers be 5:
32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

32-bit Virtual Address28-bit Physical Address

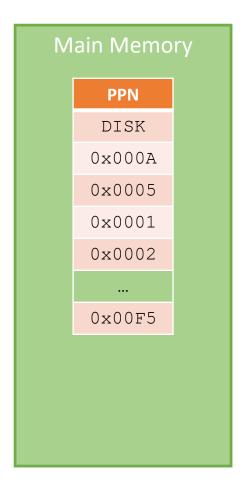
12-bit Page Offset [Index]

Virtual Address [32 bit]

Virtual Page Number		Page Offset	555	
31	12	11		0

Tag Physical Page # 0x0 0003 0x0001 0x0 0001 0x0000	TLB [2-entries big]			
	Tag	Physical Page #		
0~0 0001 0~0007	0x0 0003	0x0001		
0X0 0001 0X000A	0x0 0001	0x000A		

Physical Page Number	Page Offset	
27	12 11	0

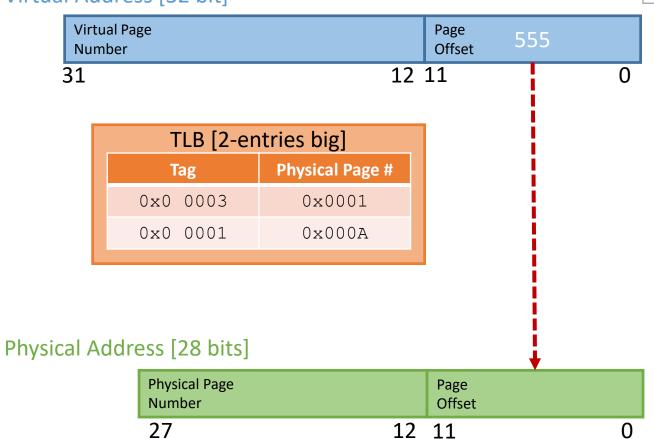


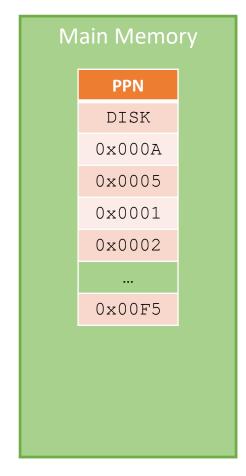
Computers be 5: 32 pit 5A, 56 / 1B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]





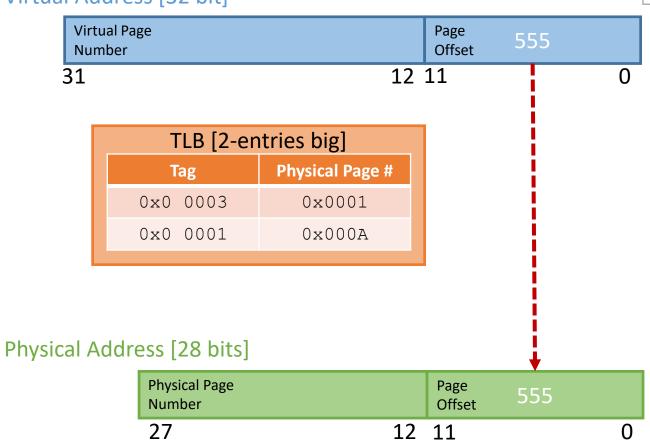
Computers be as:

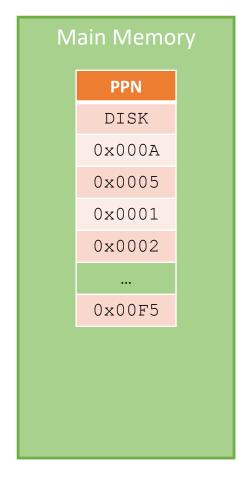
32 pit iA, .56 / IB f RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



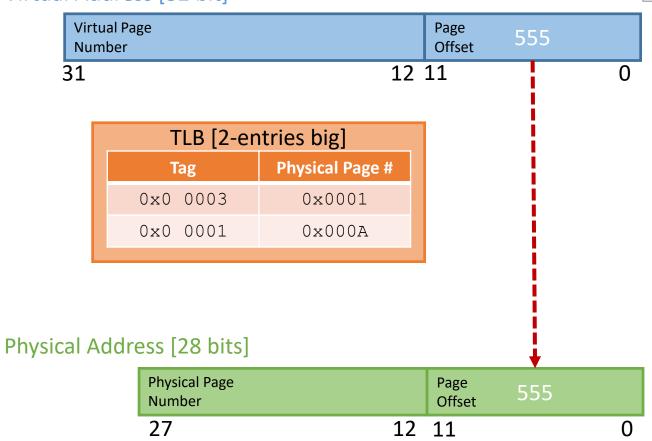


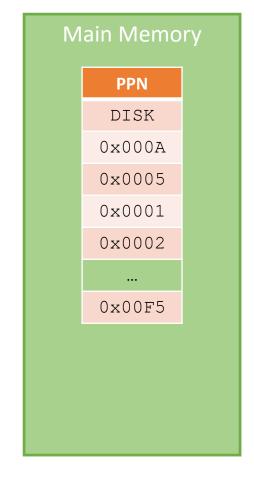
Computers be 5: 32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



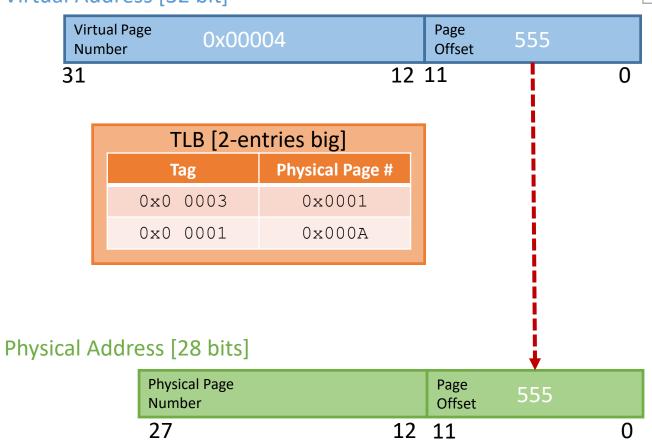


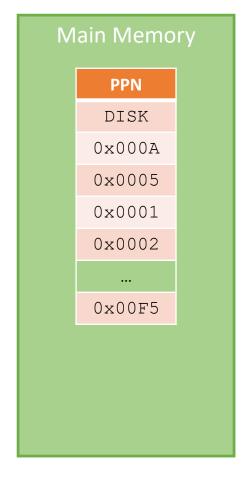
Computers be 5:
32 pit 5A, 56 / B * RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



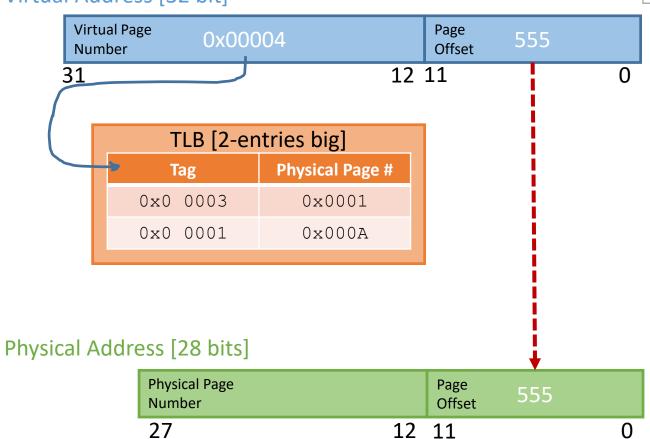


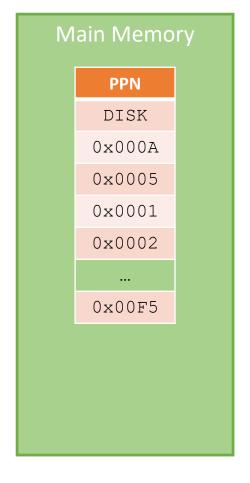
Computer Silver Silver

VA: 0x00004 555

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]





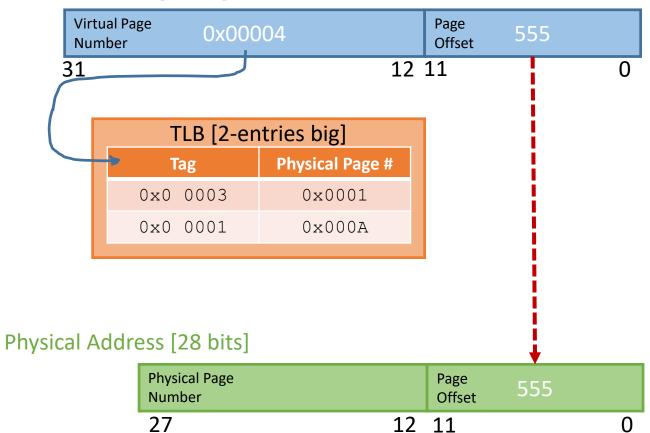
Computers be 5:
32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]



Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

Capacity Miss!

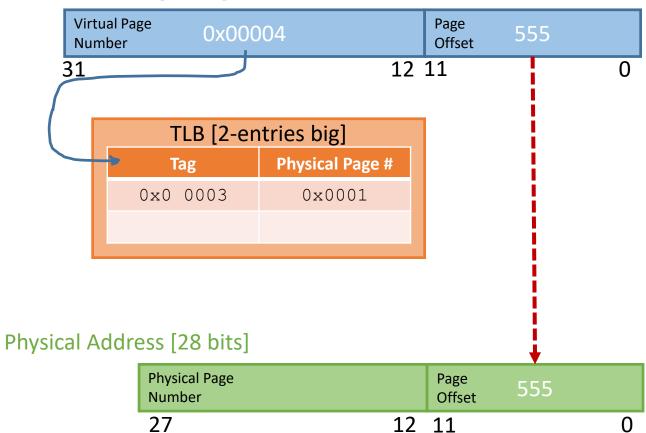
Comut risine i:
32 pit iA, 156 / IB f RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]



Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

Capacity Miss!

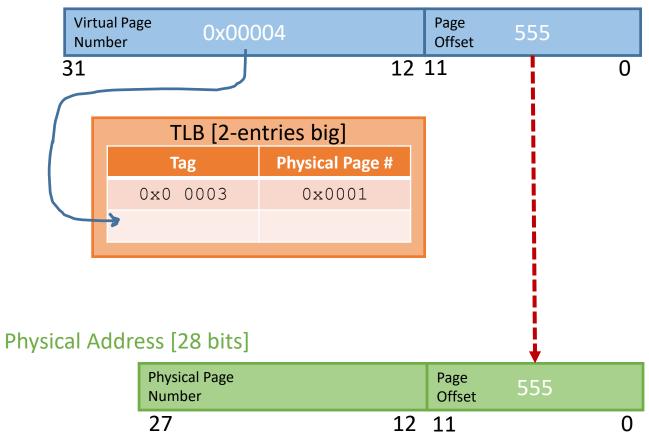
Computers be 5:
32 pit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]



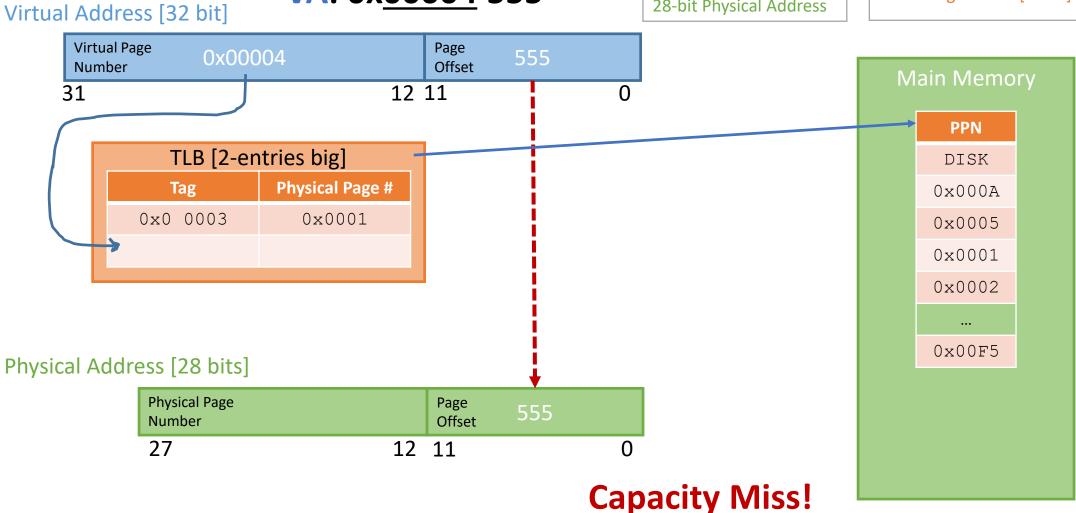
Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

Capacity Miss!

Computer Silver Silver

VA: 0x00004 555

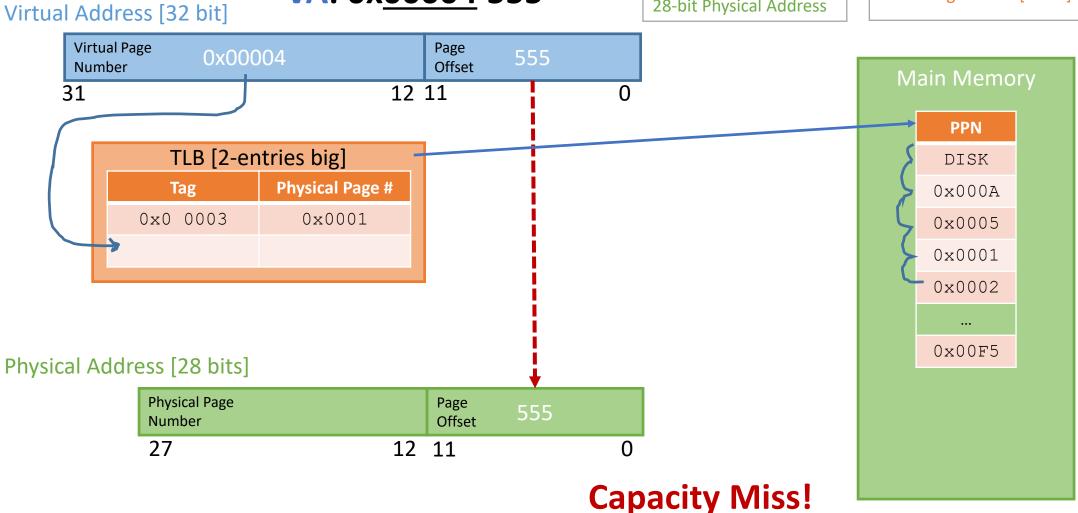
32-bit Virtual Address28-bit Physical Address



Computers be 5: 32 pit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

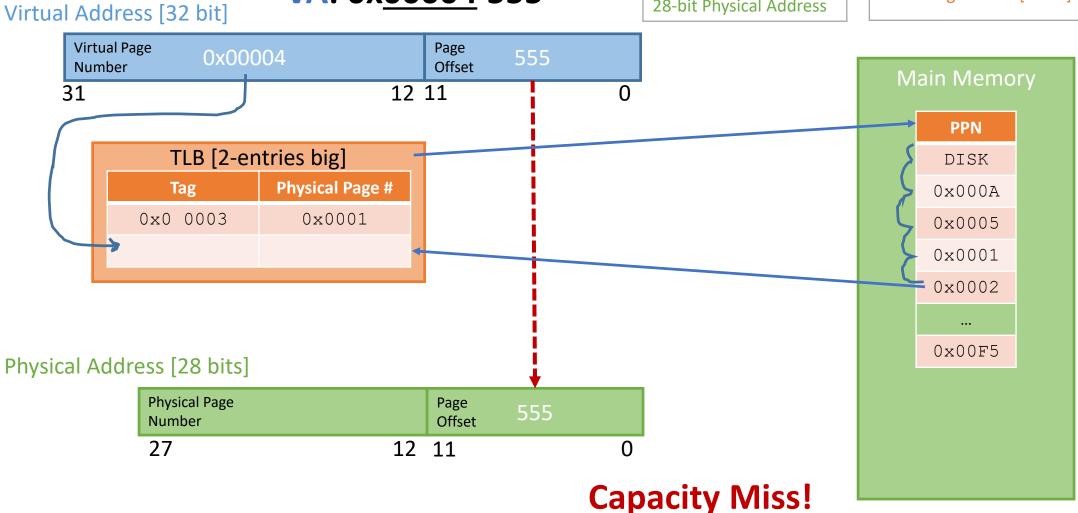
32-bit Virtual Address28-bit Physical Address



Computers be 5: 32 bit 5A, 56 4B * RAM, 4 kB pages, 2-entry TLB

VA: 0x<u>00004</u> 555

32-bit Virtual Address28-bit Physical Address

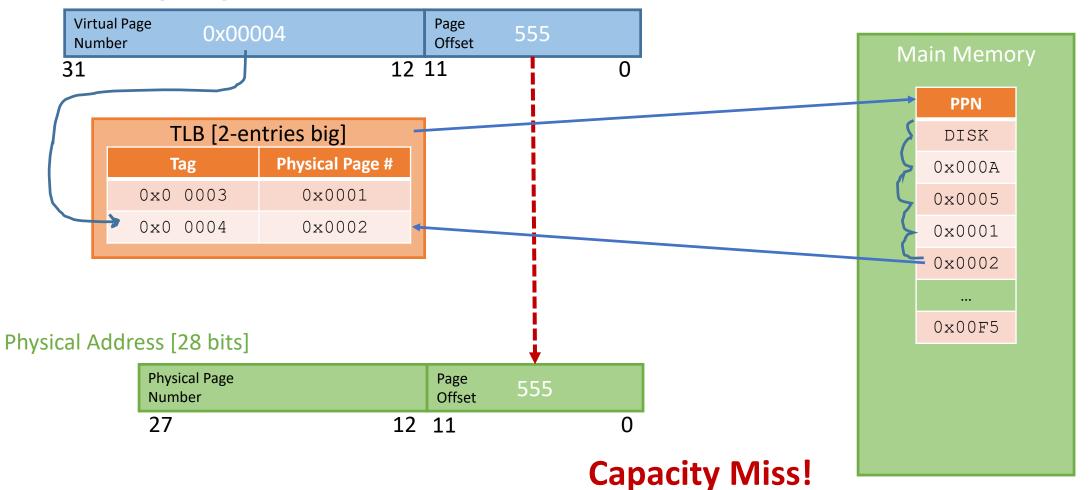


VA: 0x00004 555

Computers be 5: 32 pit 5A, 56 4B f RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address 28-bit Physical Address

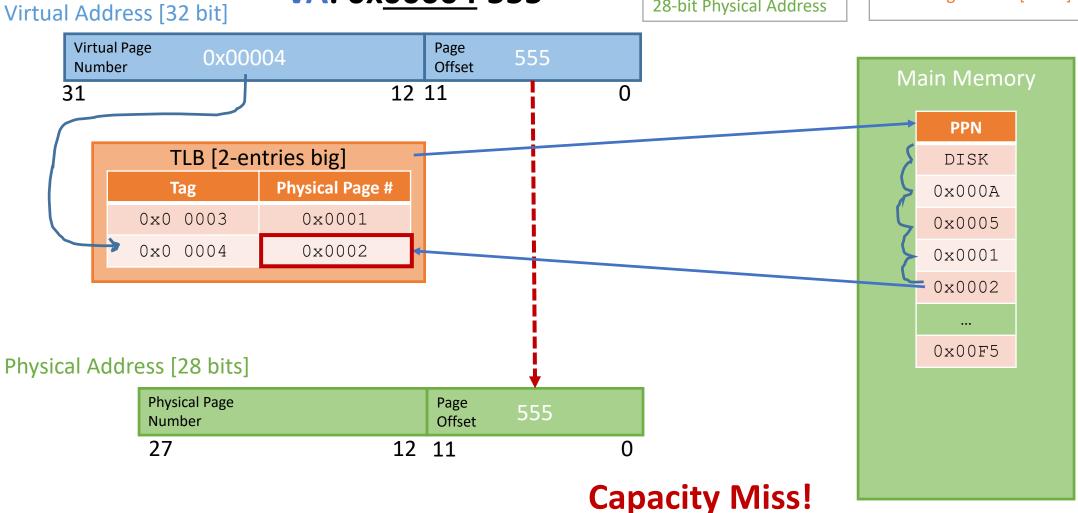
12-bit Page Offset [Index]



Computers be 5:
32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

32-bit Virtual Address28-bit Physical Address

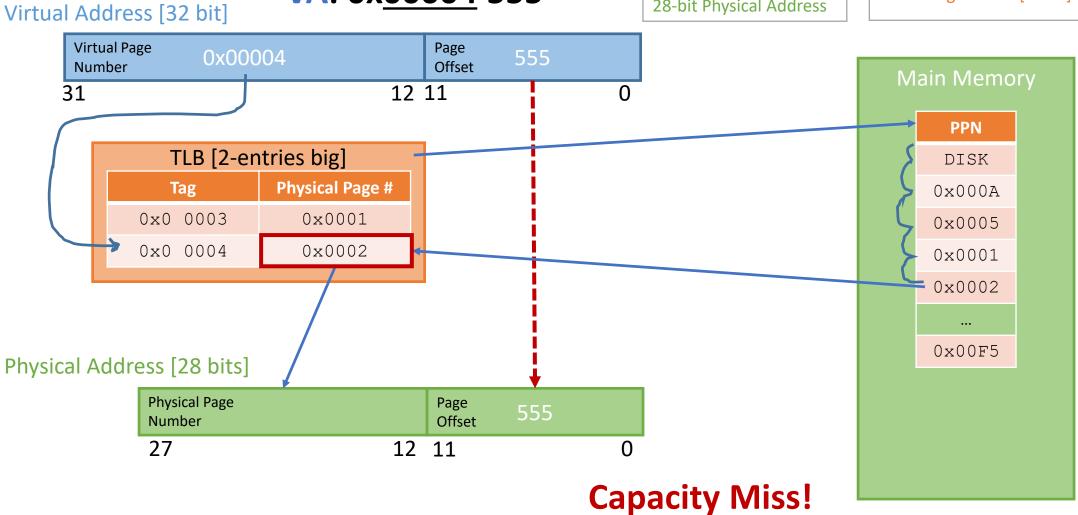


Computer to led it:

32 pit iA, 56 dB f RAM, 4 kB pages, 2-entry TLB

VA: 0x<u>00004</u> 555

32-bit Virtual Address28-bit Physical Address

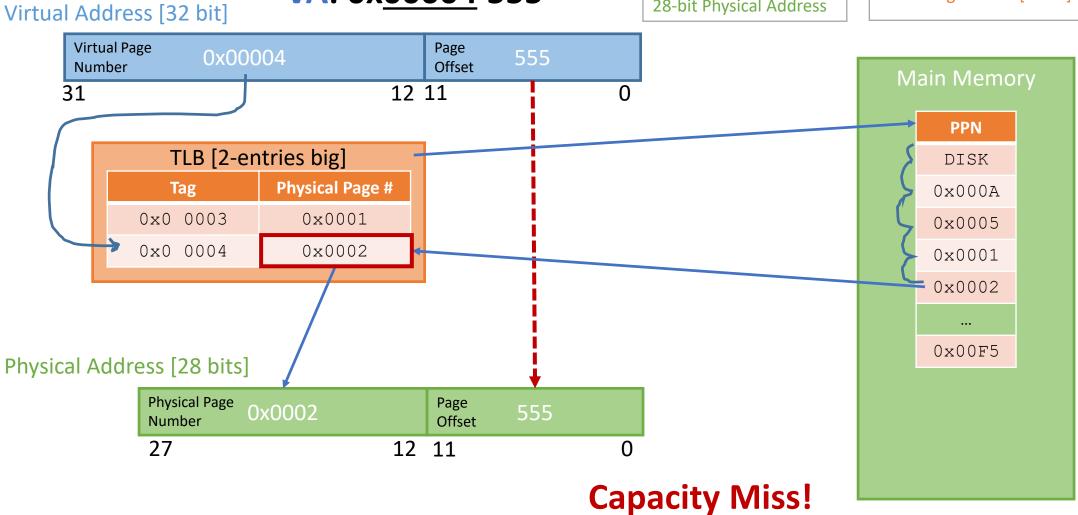


Computers be 5:

32 pit 5A, 56 4B f RAM, 4 kB pages, 2-entry TLB

VA: 0x<u>00004</u> 555

32-bit Virtual Address28-bit Physical Address

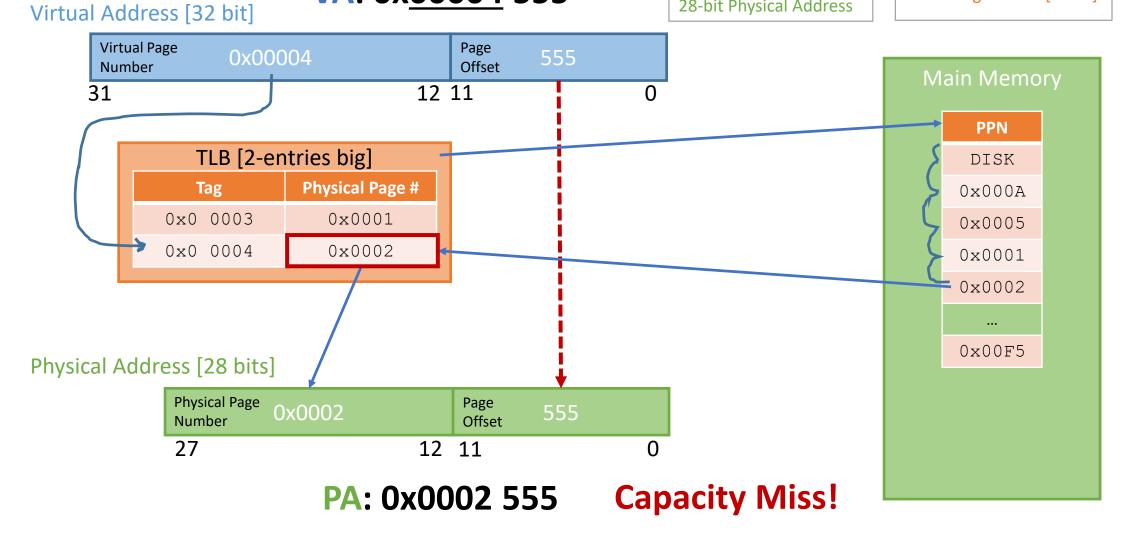


TLB Example

Com ut r 5)e ;: 32 bit SA, S6 1B * RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

32-bit Virtual Address 12-bit Page Offset [Index] 28-bit Physical Address



Computers be 5:
32 bit 5A, 56 4B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]

Virtua Numb	_	Page Offset	
31		12 11	0

Tag Physical Page	TLB [2-entries big]				
	#				
0x0 0003 0x0001					
0x0 0004 0x0002					

3 [2-entries big] Physical Page

Physical Address [28 bits]

Physical Page Number	Page Offset	
27	12 11	0

Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

Computers be 5:
32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

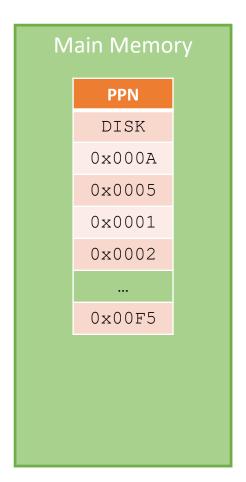
Virtual Address [32 bit]

	Virtual Page Number		Page Offset	
-	31	12	11	0

Tag Physical Page	TLB [2-entries big]				
	#				
0x0 0003 0x0001					
0x0 0004 0x0002					

Physical Address [28 bits]

Physical Page Number	Page Offset	
27	12 11	0



TLB Exampled UINCY

C(m ut r \)e ;: 32 pit SA, 56 / 1B * RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

32-bit Virtual Address 28-bit Physical Address

12-bit Page Offset [Index]

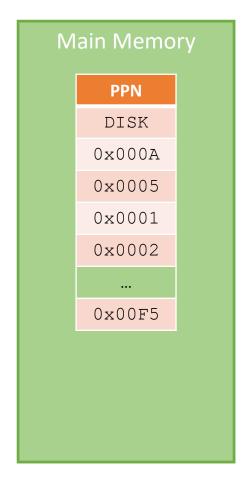
Virtual Address [32 bit]

	Virtual Page Number		Page Offset	099	
-	31	12	11		0

TLB [2-entries big]			
Tag	Physical Page #		
0x0 0003	0x0001		
0x0 0004	0x0002		

Physical Address [28 bits]

Physical Page Number	Page Offset	
27	12 11	0

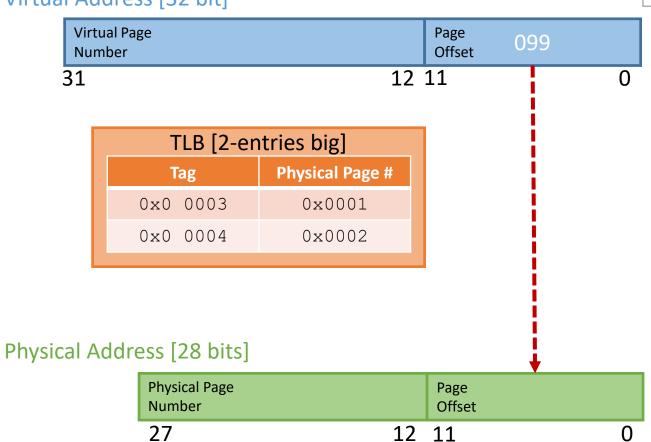


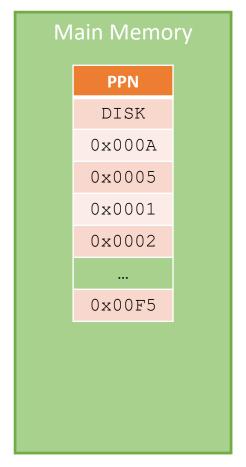
Computers be 5: 32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



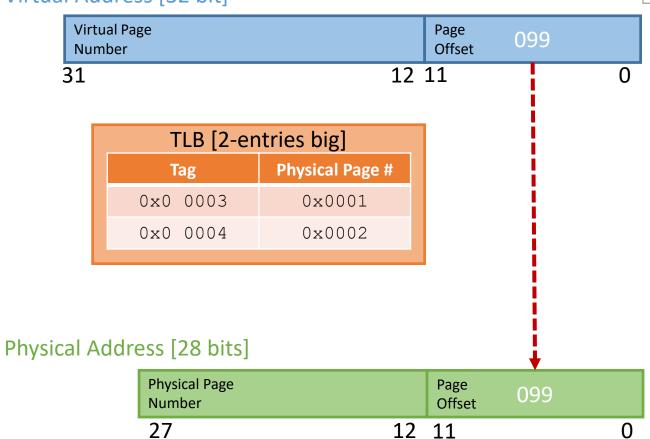


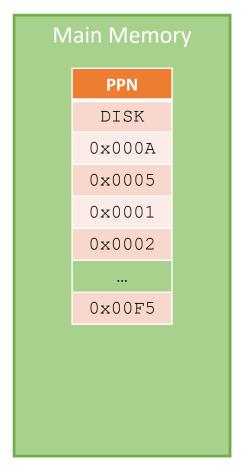
Computers be 5:
32 pit 5A, 56 / B * RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]





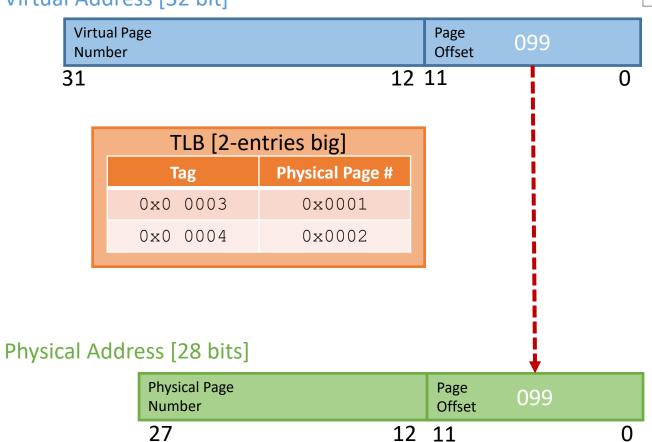
Computers be 5: 32 pit 5A, 56 / 1B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]



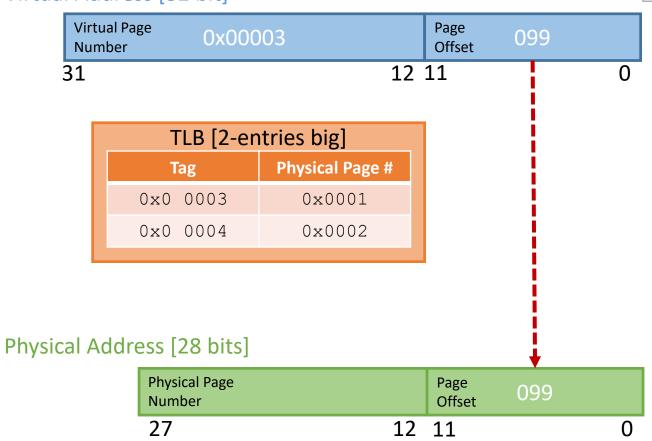
Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

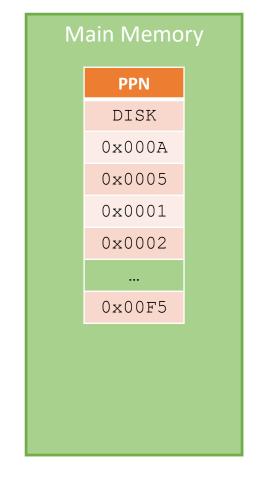
Computers be 3: 32 bit 3A, 56 / B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



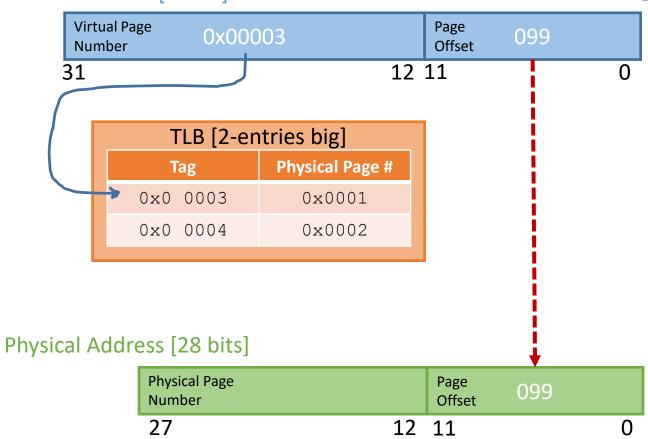


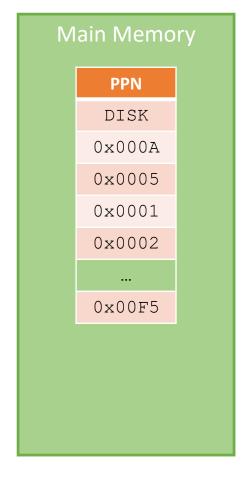
Computer Silver Silver

VA: 0x00003 099

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]





Computers be as:

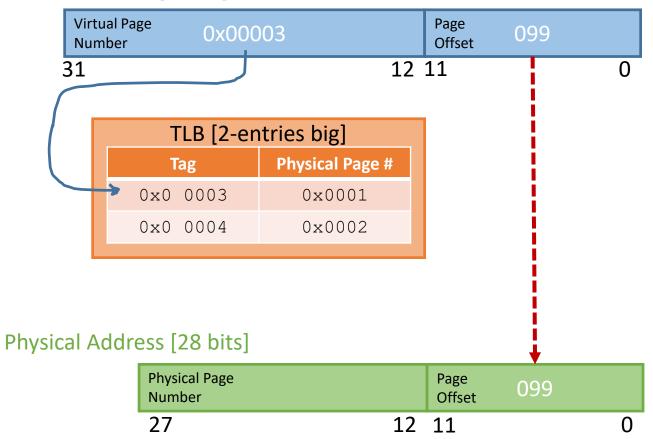
32 pit A, .56 /B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]



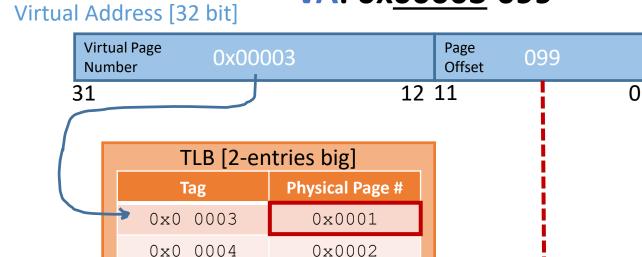
Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

Computer Silver Silver

VA: 0x<u>00003</u> 099

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



Physical Address [28 bits]

Physical Page Number		Page Offset	099	
27	12	11		0

Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

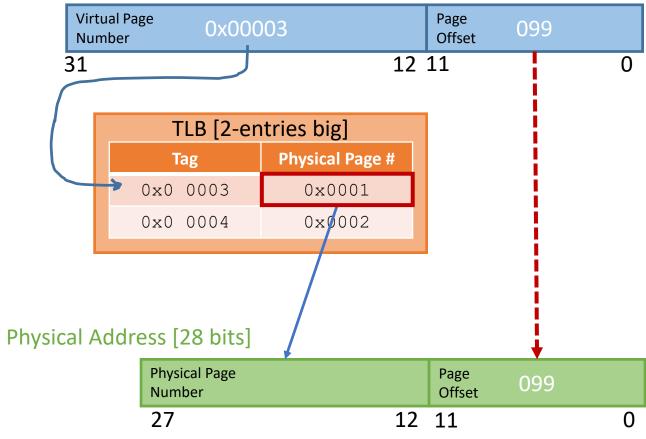
Computers be 5: 32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

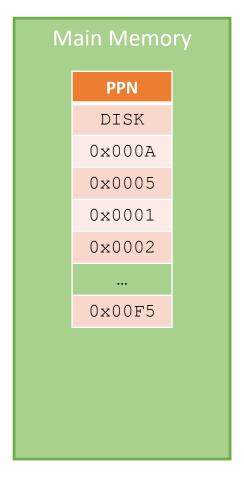
VA: 0x00003 099

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]



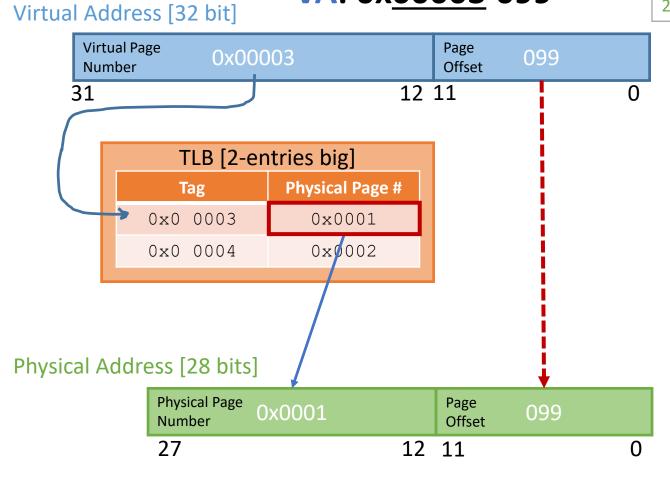


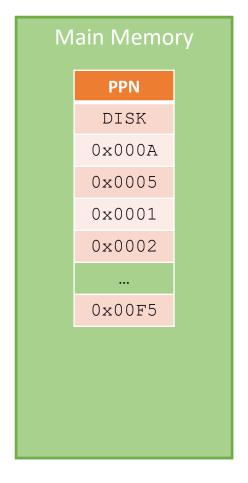
Computers be 5:
32 bit 5A, 56 4B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]





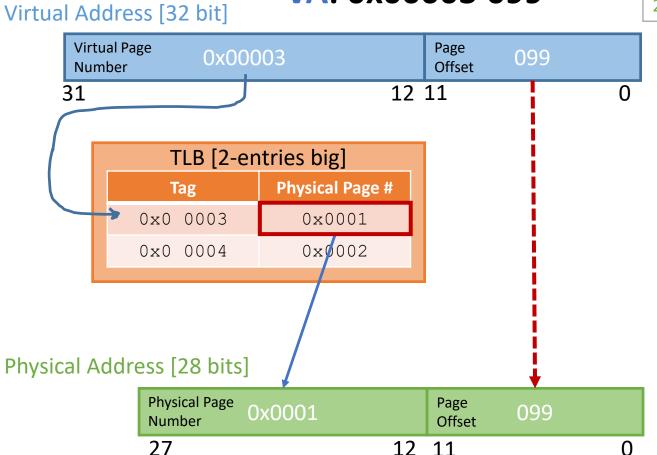
TLB Example

Com ut r 5)e ;: 32 bit SA, S6 1B * RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

32-bit Virtual Address 28-bit Physical Address

12-bit Page Offset [Index]



Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

PA: 0x0001 099

12 11

Computers be 5:
32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00000 123

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]

Virtua Numb	_	Page Offset	
31		12 11	0

Tag Physical Page # 0x0 0003 0x0001	TLB [2-entries big]				
	Tag	Physical Page #			
	0x0 0003	0x0001			
0x0 0004 0x0002	0x0 0004	0x0002			

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
...
0x00F5

Physical Address [28 bits]

P	hysical Page	Page	
N	Iumber	Offset	
2	27 12	11	0



Computers be 5: 32 pit 5A, 56 / 1B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00000 123

32-bit Virtual Address 28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]

Virtual Page Number	Page Offset	
31	12 11	0

 TLB [2-entries big]

 Tag
 Physical Page #

 0x0 0003
 0x0001

 0x0 0004
 0x0002

Q: What is the PA associated with this VA?

Physical Address [28 bits]

Physical Page Number		Page Offset	
27	12	11	0

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
...
0x00F5

Computers be 5:
32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00000 123

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Main Memory

Virtual Address [32 bit]

	Virtual Page Number		Page Offset	
-	31	12	11	0

TLB [2-entries big]			
Tag	Physical Page #		
0x0 0003	0x0001		
0x0 0004	0x0002		

12 11 0

PPN
DISK
0x000A
0x0005
0x0001
0x0002
...
0x00F5

Physical Address [28 bits]

Physical Page Number	Page Offset	
27	12 11	0

Computers be 5: 32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00000 123

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]

	Virtual Page Number	Page Offset	123	
_	31 12	11		0

TLB [2-entries big]			
Tag	Physical Page #		
0x0 0003	0x0001		
0x0 0004	0x0002		

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
....
0x00F5

Physical Address [28 bits]

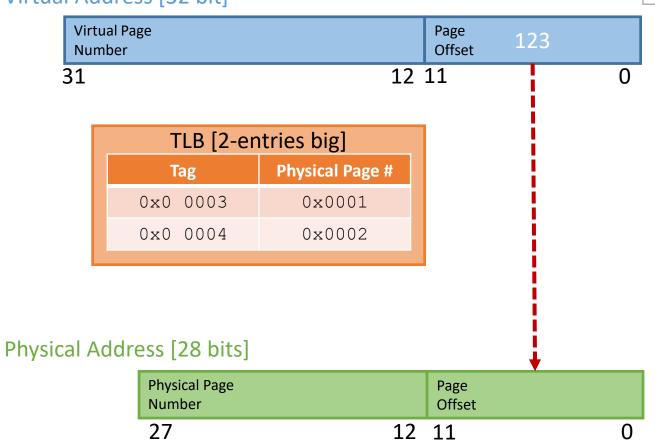
Physical Page Number	Page Offset	
27	12 11	0

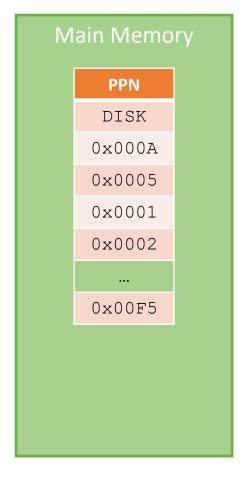
Computers be 5: 32 bit 5A, 56 4B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00000 123

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



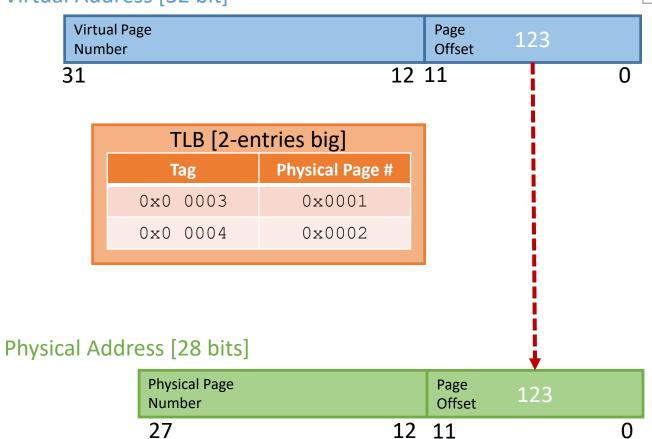


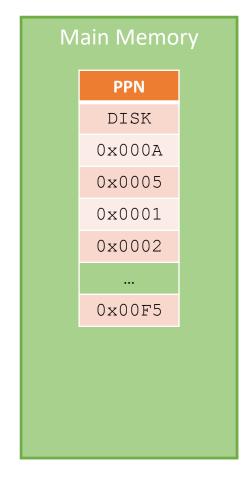
Computers be 5: 32 pit 5A, 56 4B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00000 123

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



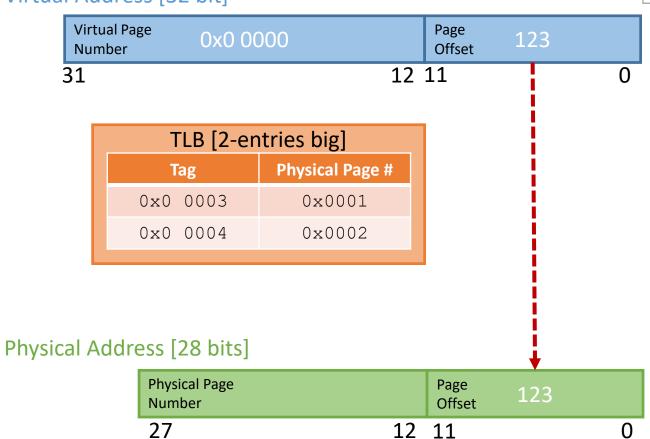


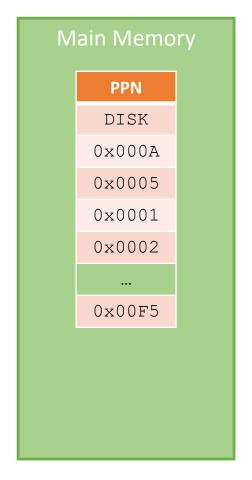
Comut risine i:
32 pit iA, .56 /B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00000 <u>123</u>

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]



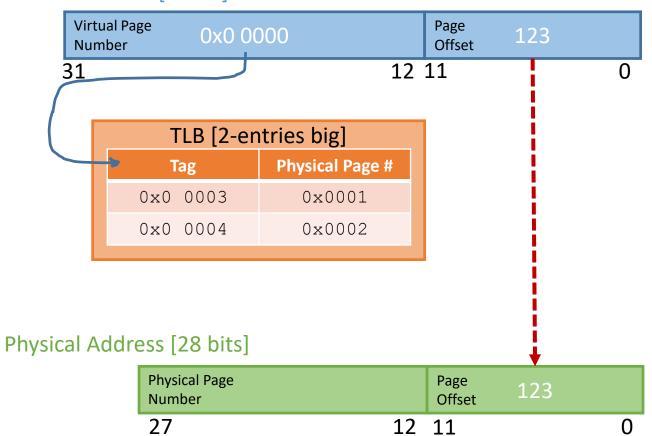


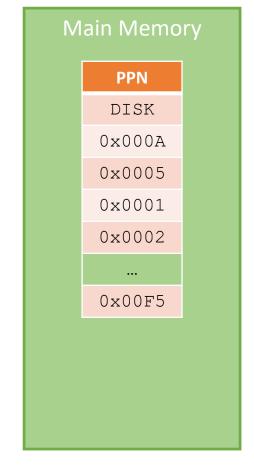
Computers be 5:
32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00000 <u>123</u>

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]





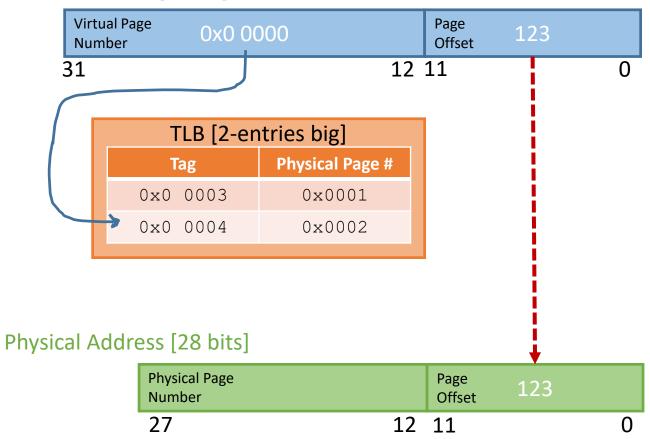
Computers be 5:
32 bit 5A, 56 4B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00000 123

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]



Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

TLB Miss!

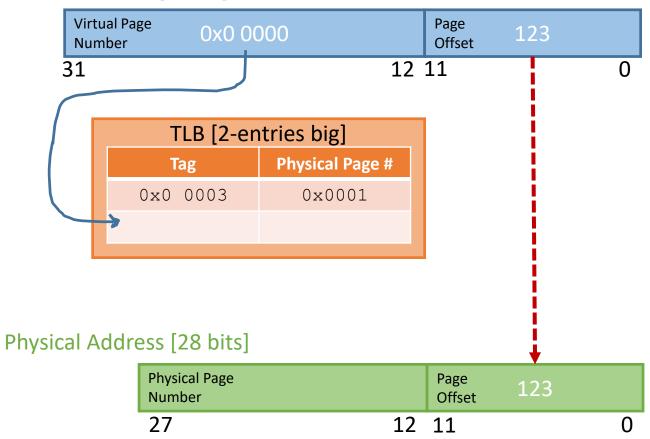
Computers be 5:
32 pit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00000 123

32-bit Virtual Address28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]



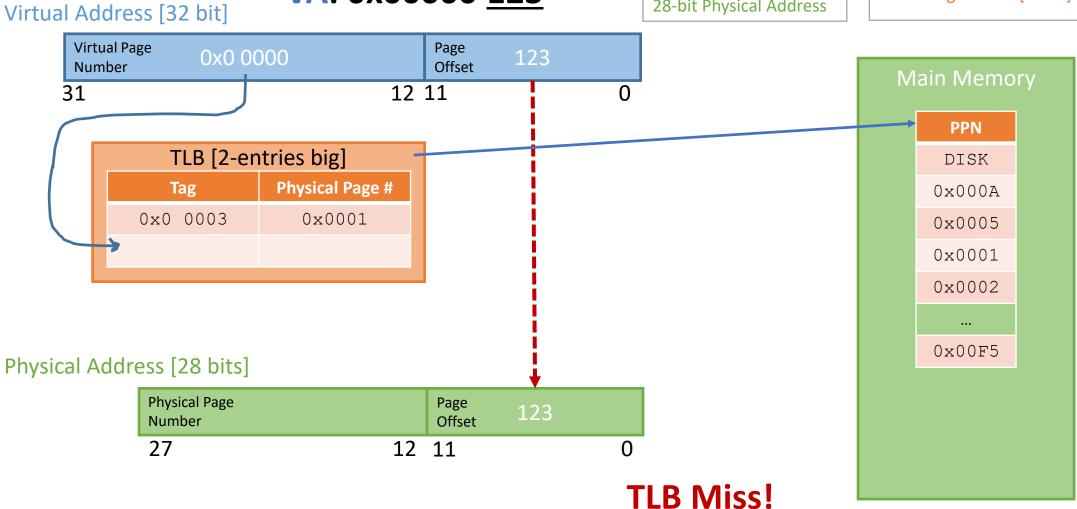
Main Memory PPN DISK 0x000A 0x0005 0x0001 0x0002 0x00F5

TLB Miss!

Computers be 5: 32 bit 5A, 56 4B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00000 <u>123</u>

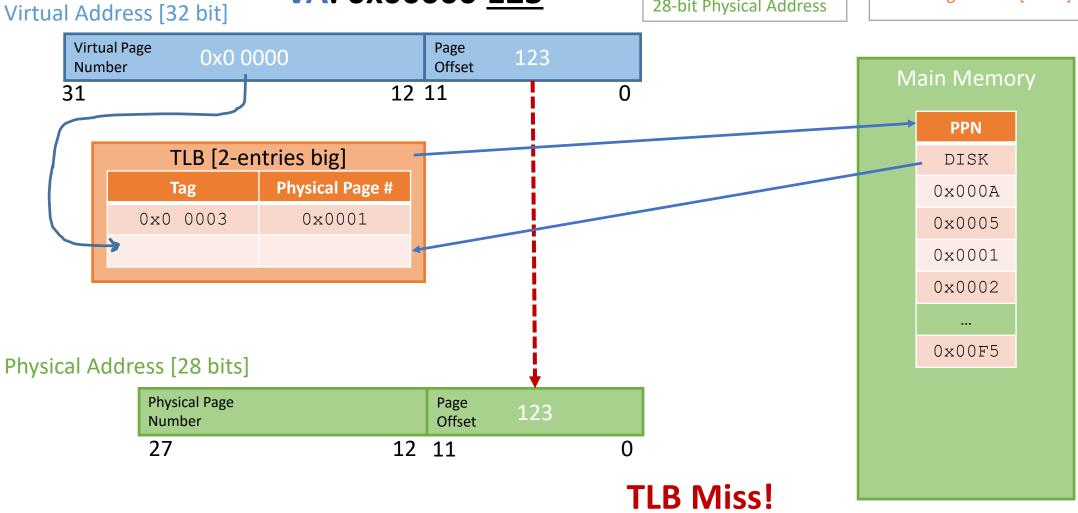
32-bit Virtual Address28-bit Physical Address



Computers be 5: 32 pit 5A, 56 /B FRAM, 4 kB pages, 2-entry TLB

VA: 0x00000 <u>123</u>

32-bit Virtual Address28-bit Physical Address

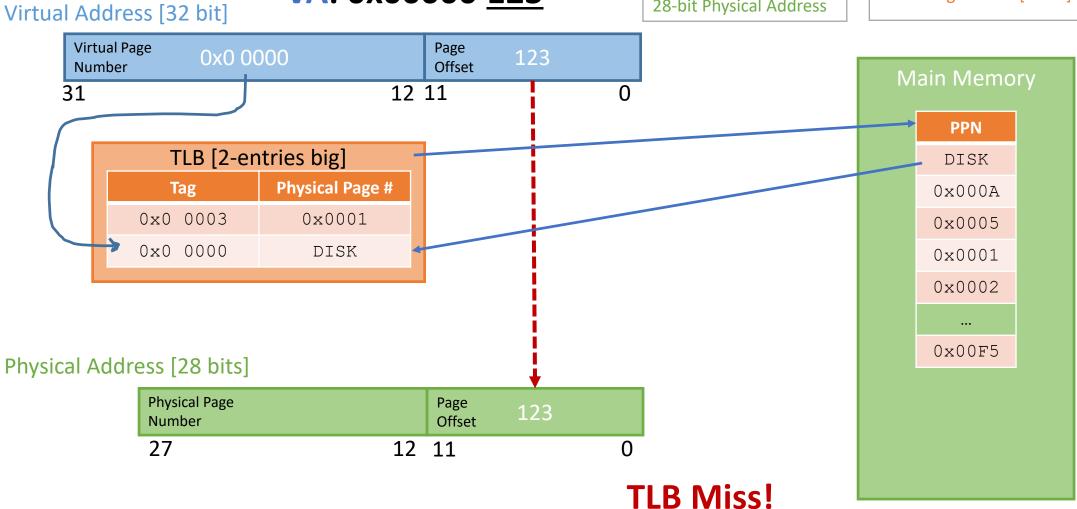


Computer to be is:

32 bit iA, .56 4B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00000 <u>123</u>

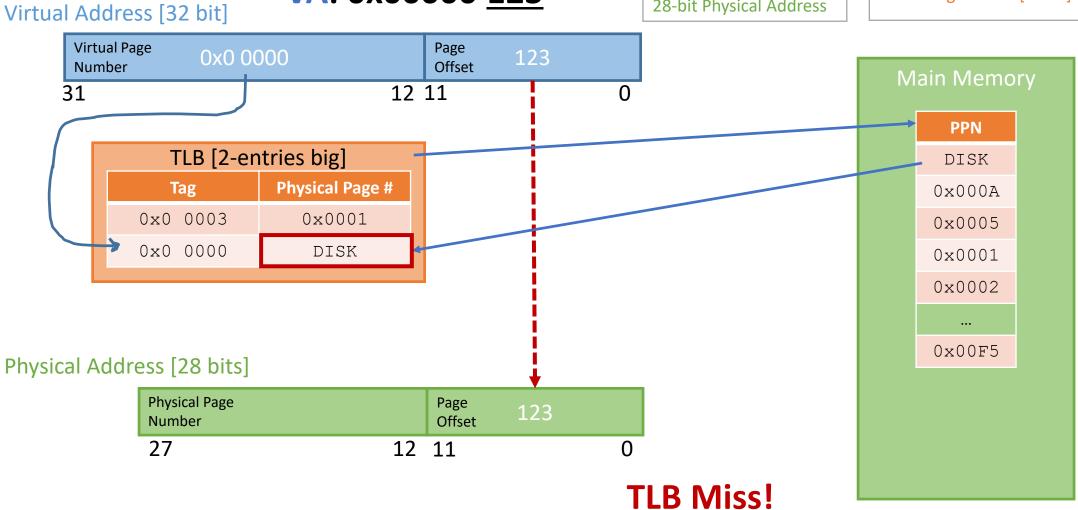
32-bit Virtual Address28-bit Physical Address



Comut replements of the company of t

VA: 0x00000 123

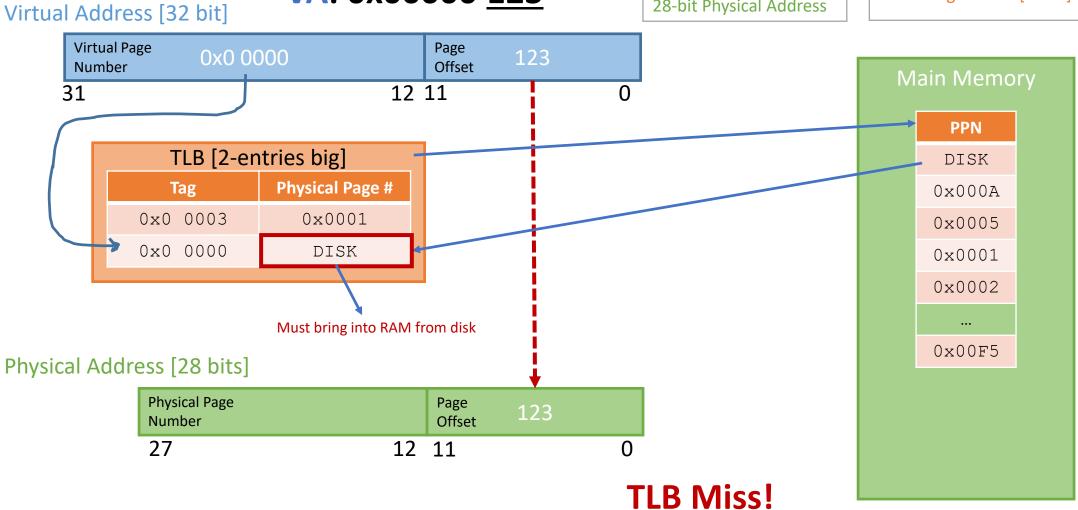
32-bit Virtual Address28-bit Physical Address



Computers be 5: 32 bit 5A, 56 dB FRAM, 4 kB pages, 2-entry TLB

VA: 0x00000 <u>123</u>

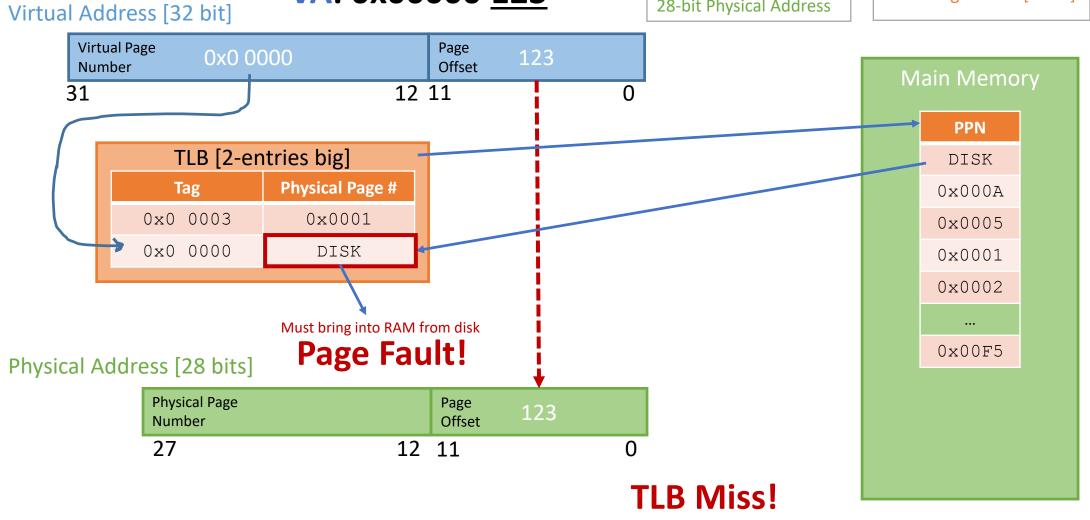
32-bit Virtual Address
28-bit Physical Address



Computers be 5: 32 pit 5A, 56 / 1B f RAM, 4 kB pages, 2-entry TLB

VA: 0x00000 123

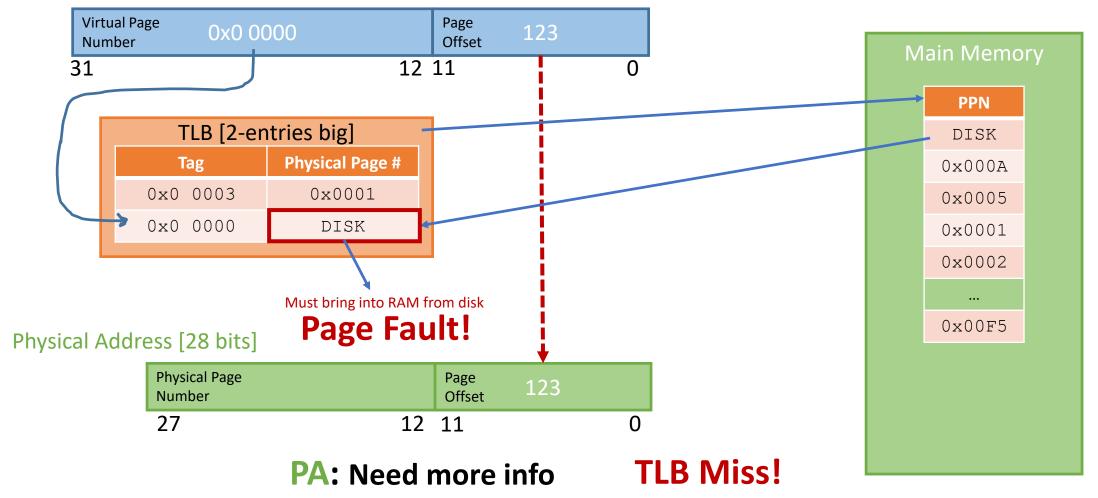
32-bit Virtual Address28-bit Physical Address



Computer Silver Silver

VA: 0x00000 <u>123</u>

32-bit Virtual Address
28-bit Physical Address
12-bit Page Offset [Index]



Quincy Flint

References Quincy Flint

- David Black-Schaffer: Lecture Series on Virtual Memory
- Patterson, Hennessy: Computer Organization and Design: the Hardware/Software Interface
- Intel Hardware Data-Sheets
- Linux: Anatomy of a Program in Memory