

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

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TLB Example

TLB Example

Quincy Flint

Computer Specs:
32-bit IA, 156 MB RAM, 4 kB pages, 2-entry TLB



32-bit Virtual Address
28-bit Physical Address

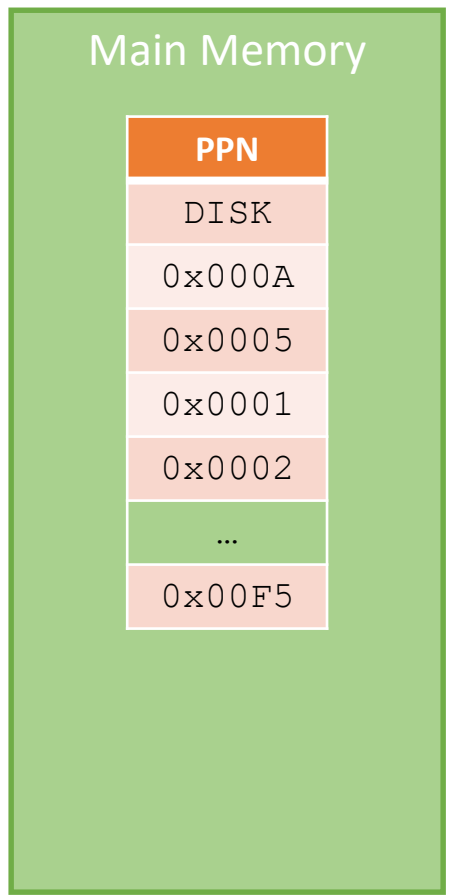
12-bit Page Offset [Index]

Virtual Address [32 bit]



TLB [2-entries big]	
Tag	Physical Page #

Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:
32-bit SA, 56 MB RAM, 4 kB pages, 2-entry TLB



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

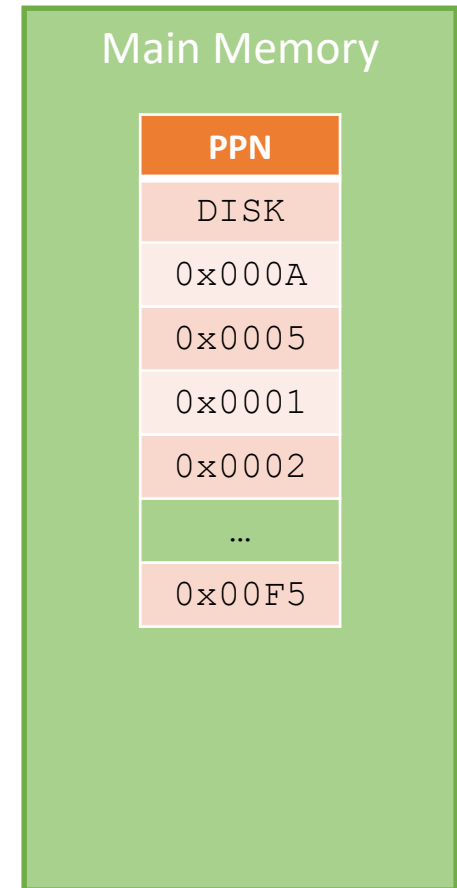
Virtual Address [32 bit]



TLB [2-entries big]

Tag	Physical Page #

Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:
32-bit SA, 156 MB RAM, 4 kB pages, 2-entry TLB



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]

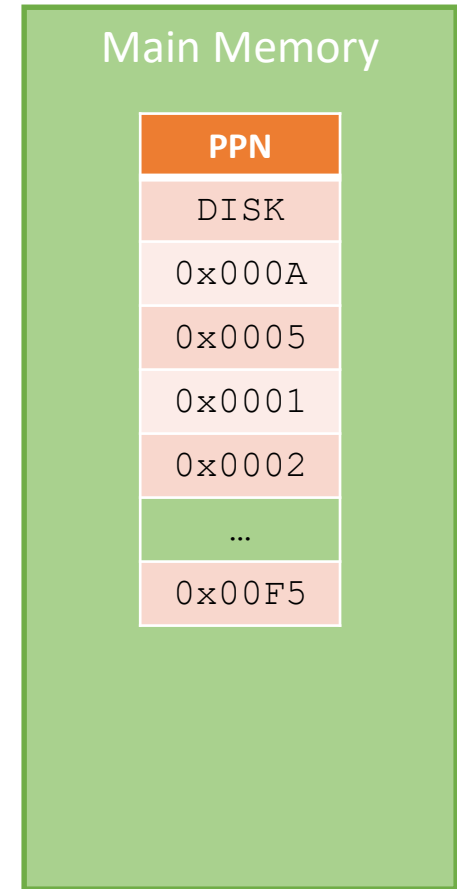


TLB [2-entries big]

Tag	Physical Page #
0x0 0001	0x000A

1 entry already filled

Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 156 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

Virtual Address [32 bit]



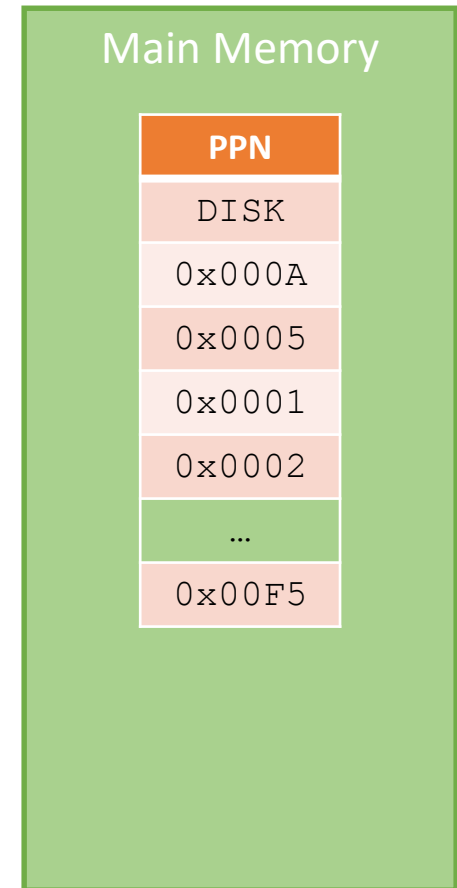
TLB [2-entries big]	
Tag	Physical Page #
0x0 0001	0x000A

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Example

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Computer Specs:

32-bit VA, 156 MB RAM, 4 kB pages, 2-entry TLB



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

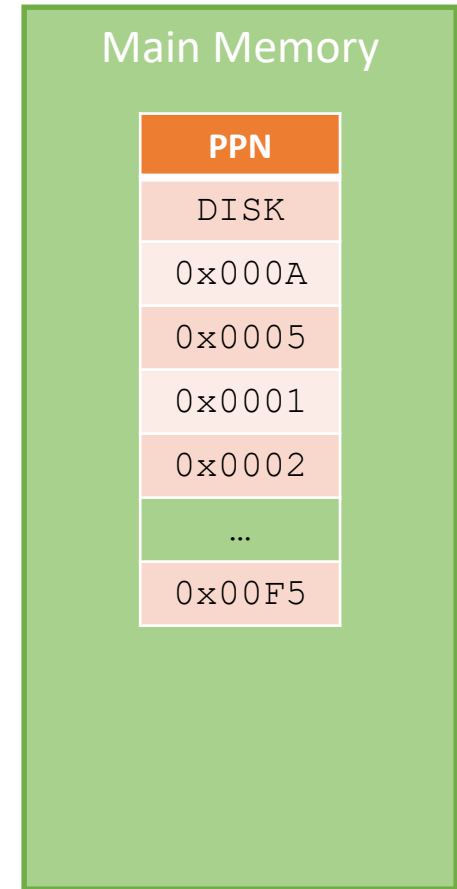
VA: 0x00003 103

Virtual Address [32 bit]



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

Physical Address [28 bits]



TLB Example

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Computer Specs:
32-bit VA, 156 MB RAM, 4 kB pages, 2-entry TLB

Virtual Address [32 bit]

VA: 0x00003 103

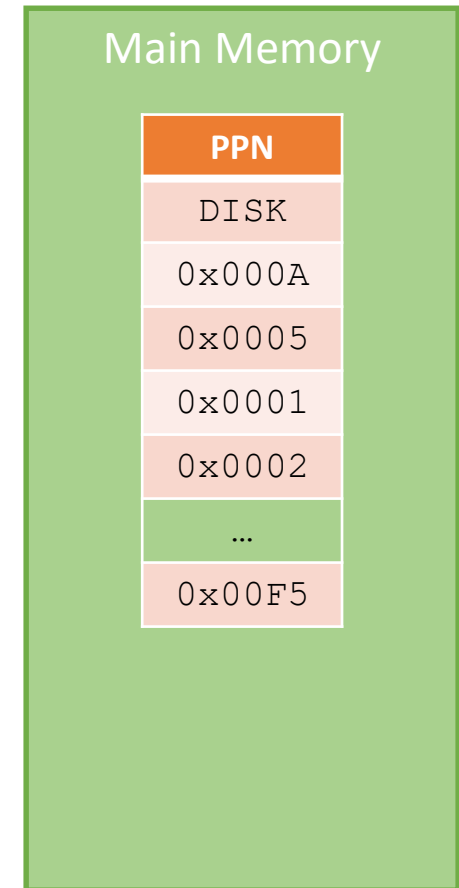
32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



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

Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:
32-bit ISA, 156 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

Virtual Address [32 bit]



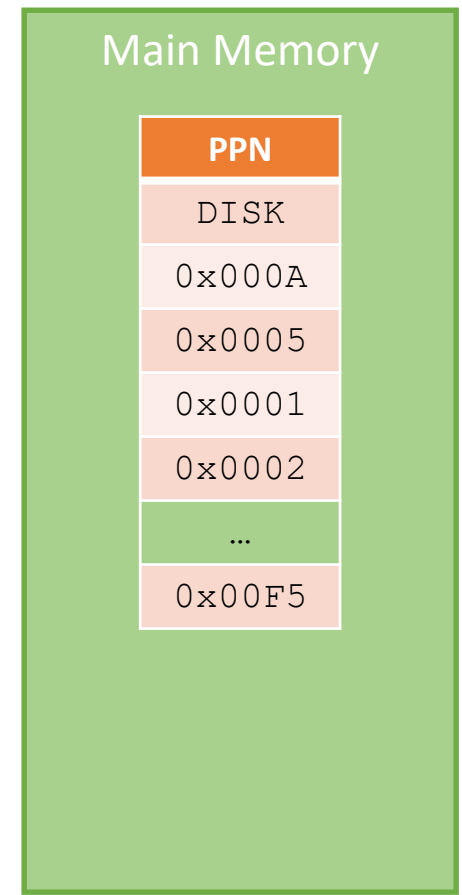
32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

TLB [2-entries big]

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Physical Address [28 bits]



TLB Example

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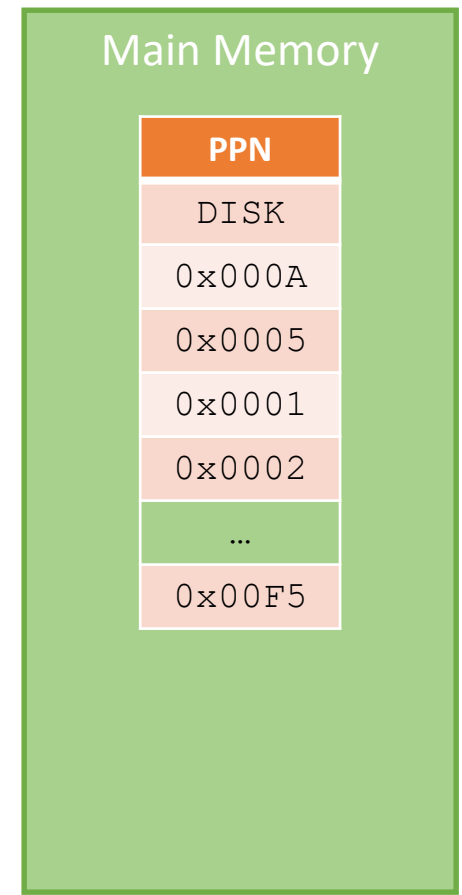
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12-bit Page Offset [Index]



TLB [2-entries big]	
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Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB of RAM, 4 kB pages, 2-entry TLB



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00003 103

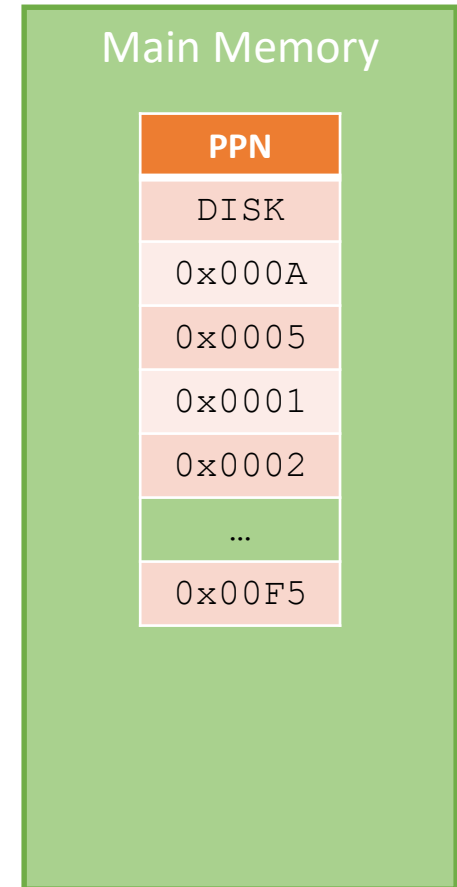
Virtual Address [32 bit]



TLB [2-entries big]

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Physical Address [28 bits]



TLB Example

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Computer Specs:
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Virtual Address [32 bit]



TLB [2-entries big]

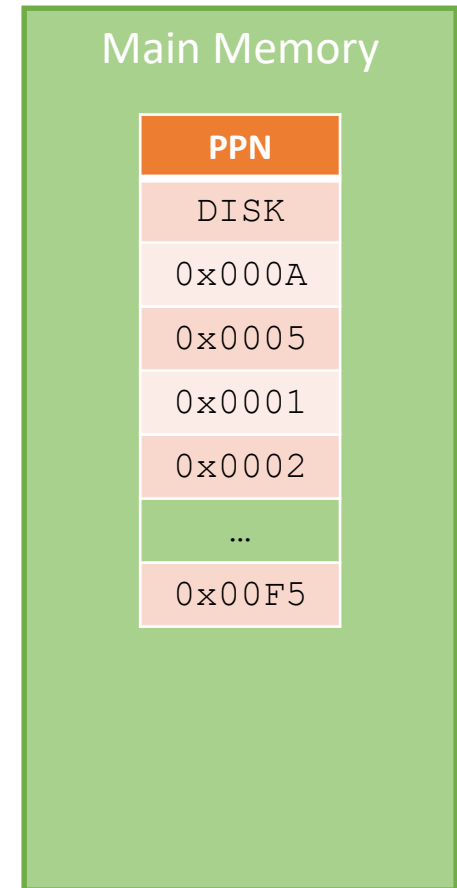
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0x0 0001	0x000A

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



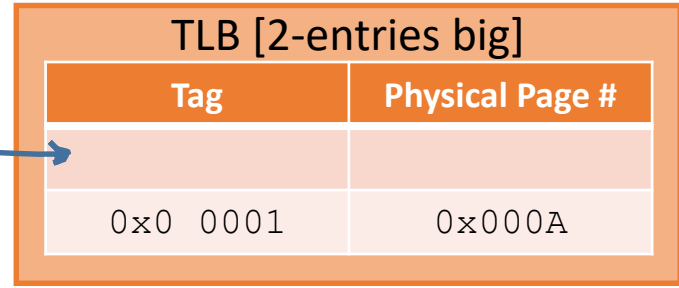
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VA: 0x00003 103

Virtual Address [32 bit]

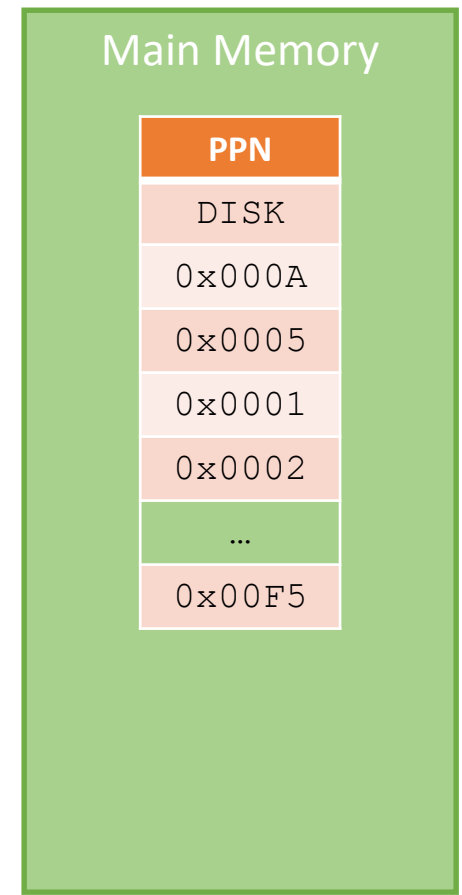


Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



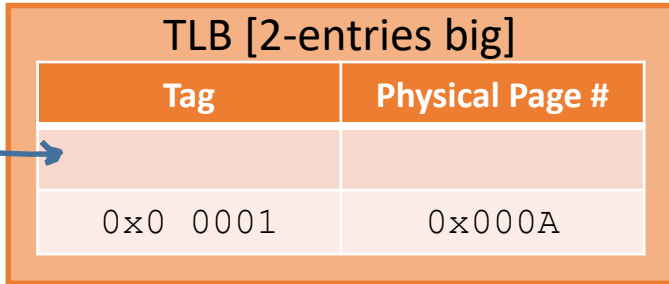
TLB Example

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Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

Virtual Address [32 bit]

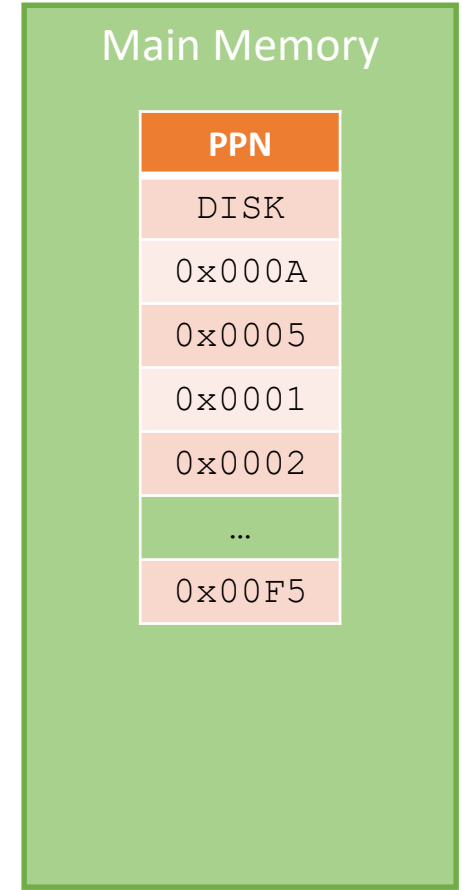


Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



Compulsory Miss!

TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

Virtual Address [32 bit]



TLB [2-entries big]

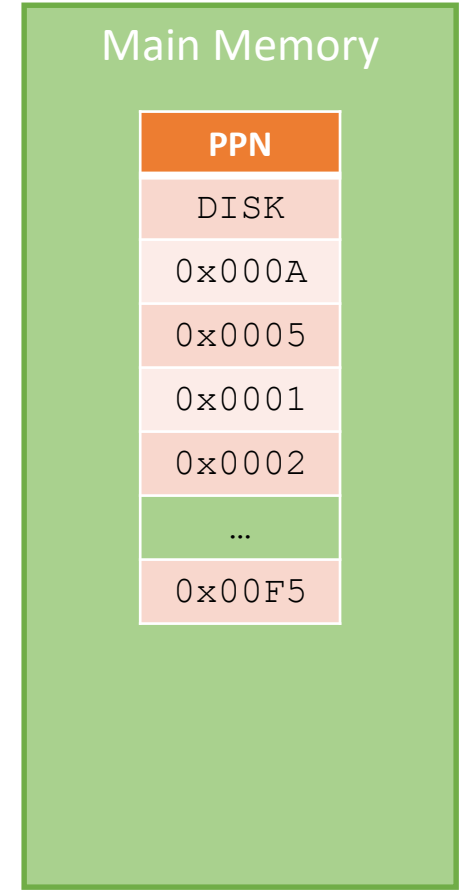
Tag	Physical Page #
0x0 0003	
0x0 0001	0x000A

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



Compulsory Miss!

TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

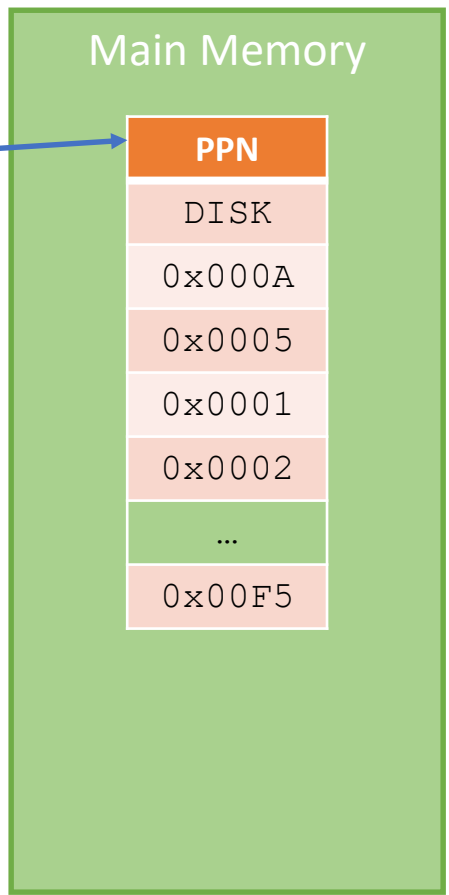
Virtual Address [32 bit]

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	
0x0 0001	0x000A



Physical Address [28 bits]



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TLB Example

Quincy Flint

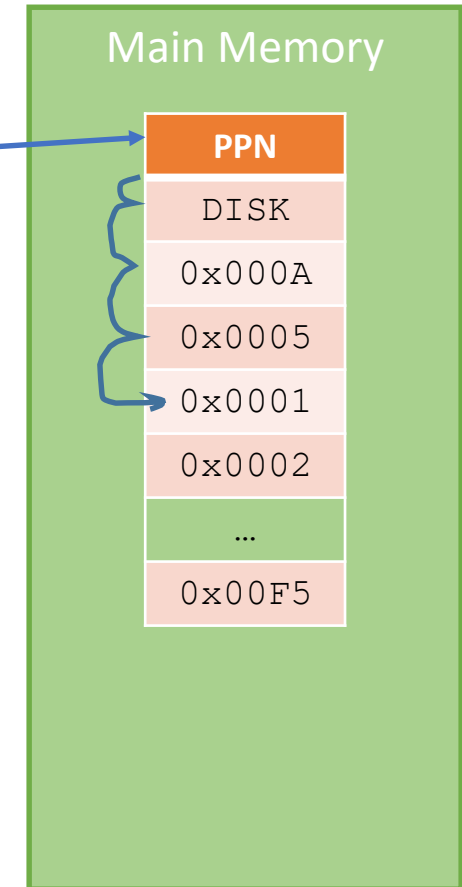
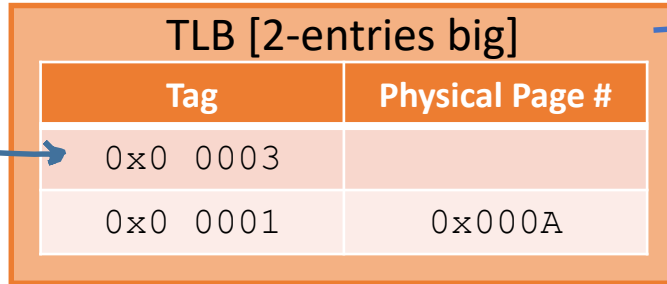
Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

Virtual Address [32 bit]

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



Physical Address [28 bits]



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TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

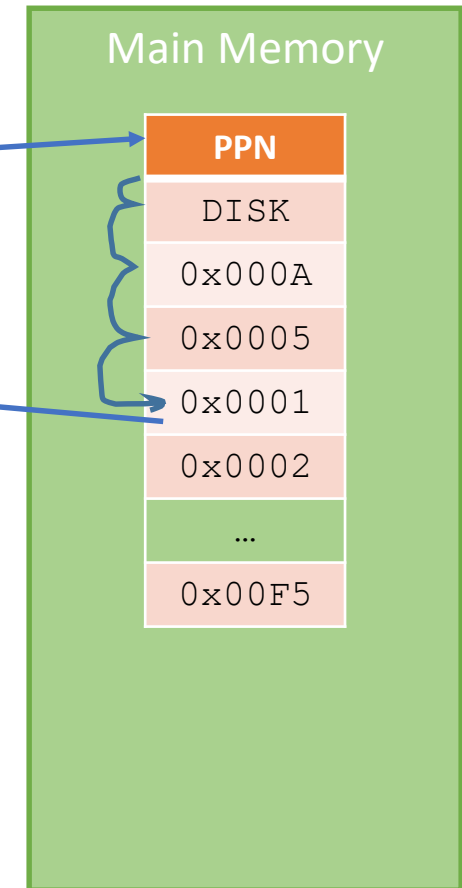
Virtual Address [32 bit]

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0001	0x000A



Physical Address [28 bits]



Compulsory Miss!

TLB Example

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Computer Specs:

32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

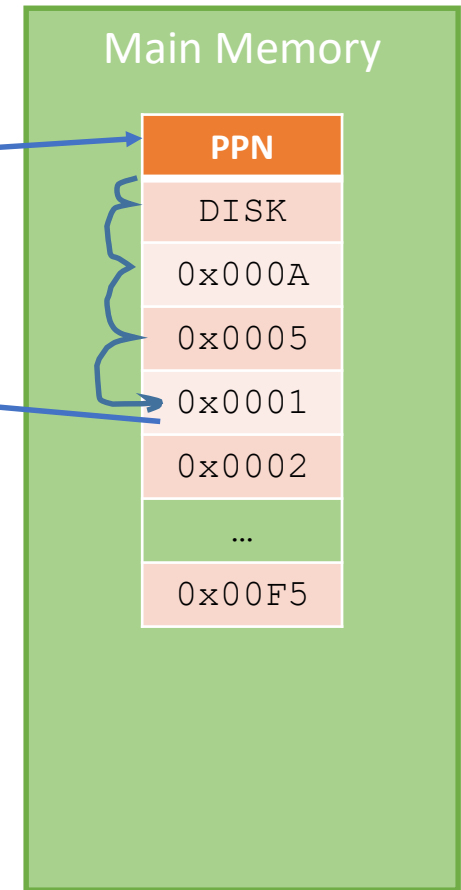
Virtual Address [32 bit]



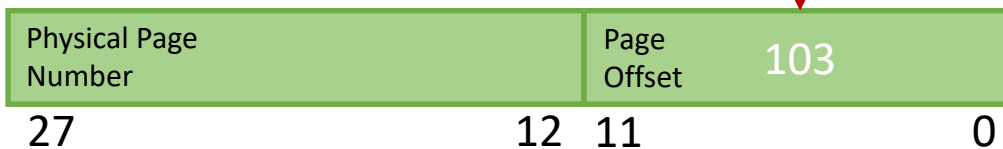
32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0001	0x000A



Physical Address [28 bits]



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TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

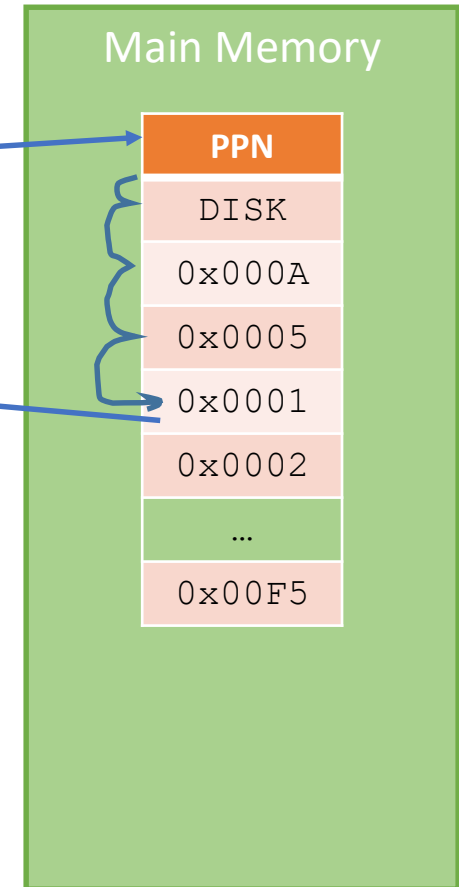
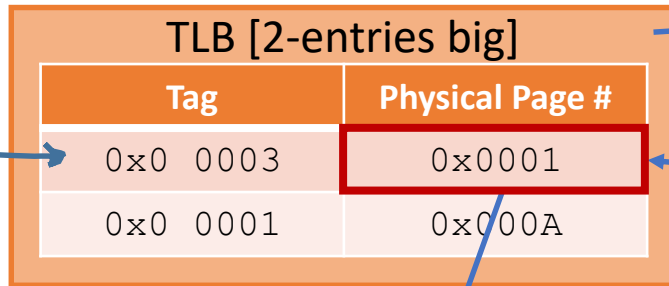
VA: 0x00003 103

Virtual Address [32 bit]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



Physical Address [28 bits]



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TLB Example

Quincy Flint

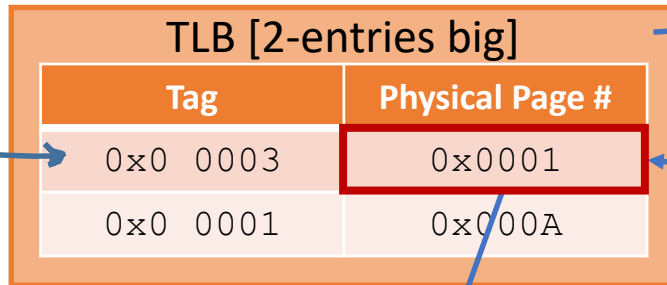
Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 103

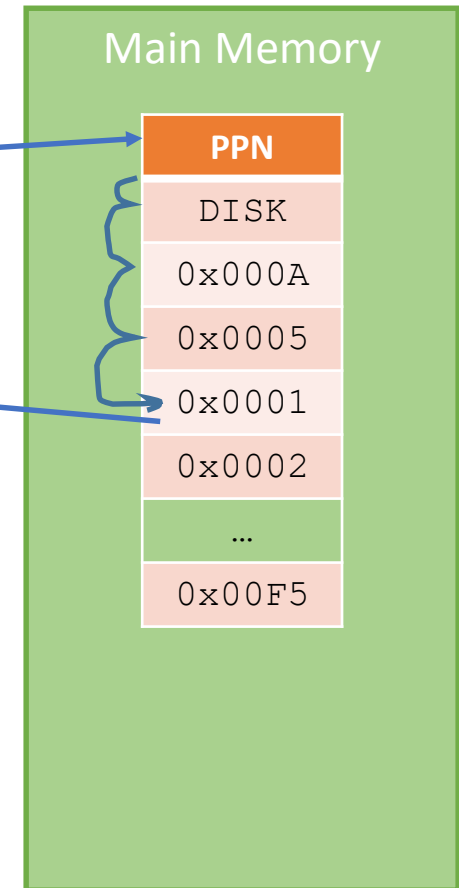
Virtual Address [32 bit]

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



Physical Address [28 bits]



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TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

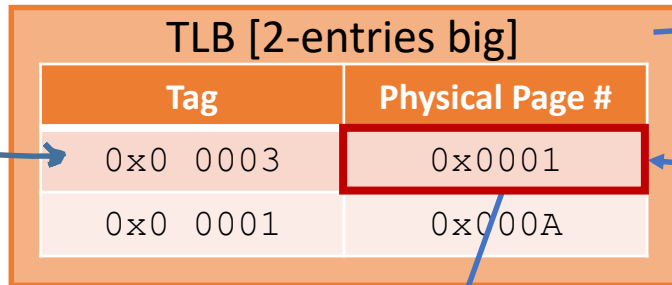


32-bit Virtual Address
28-bit Physical Address

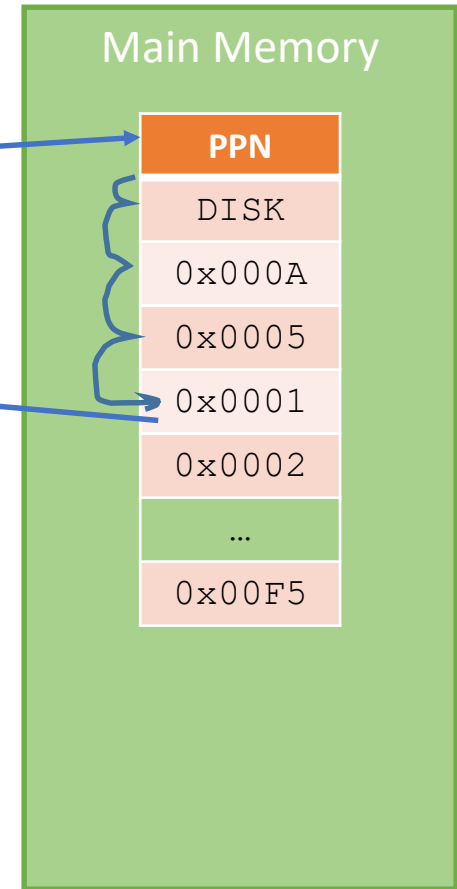
12-bit Page Offset [Index]

VA: 0x00003 103

Virtual Address [32 bit]



Physical Address [28 bits]



PA: 0x001 103 **Compulsory Miss!**

TLB Example

Quincy Flint

Computer Specs:
32-bit ISA, 156 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

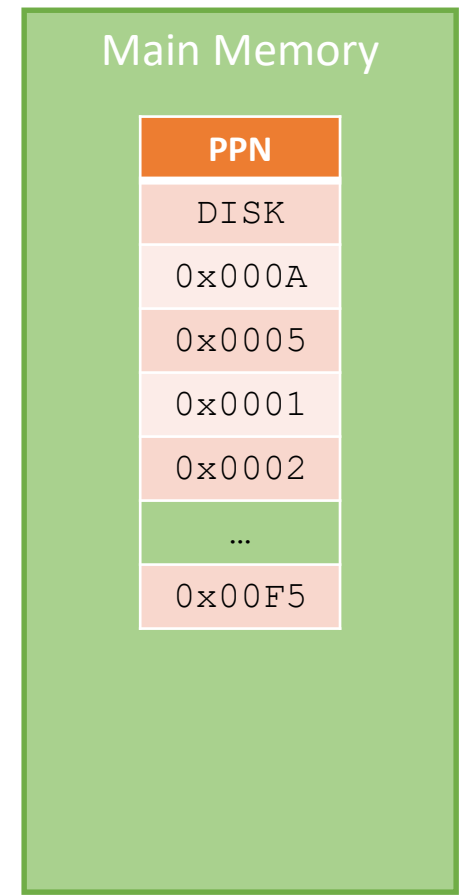
Virtual Address [32 bit]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0001	0x000A



Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

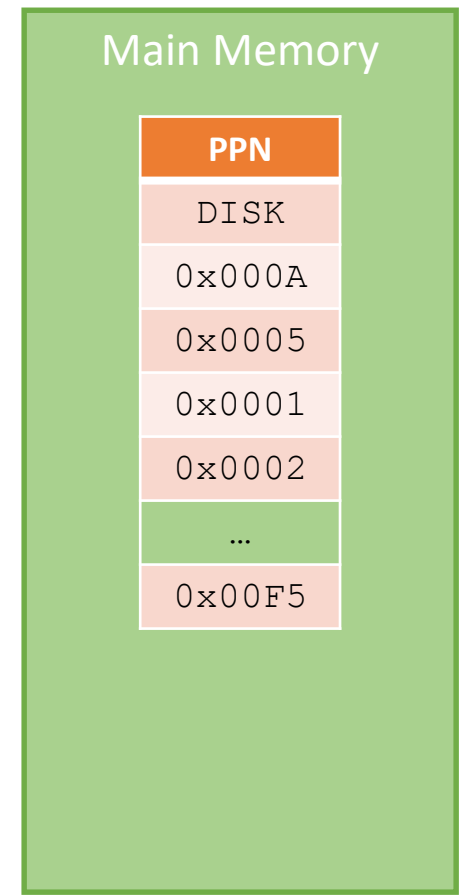
Virtual Address [32 bit]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0001	0x000A



Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:
32-bit ISA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

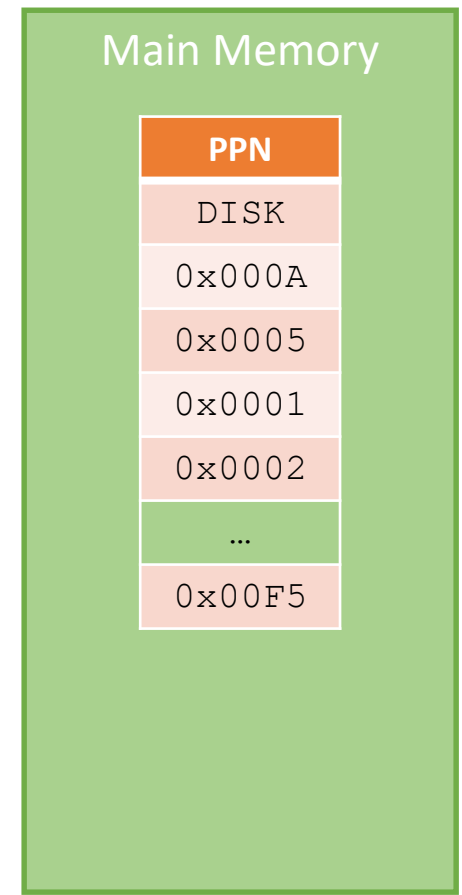
Virtual Address [32 bit]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0001	0x000A



Physical Address [28 bits]



TLB Example

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32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

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Virtual Address [32 bit]



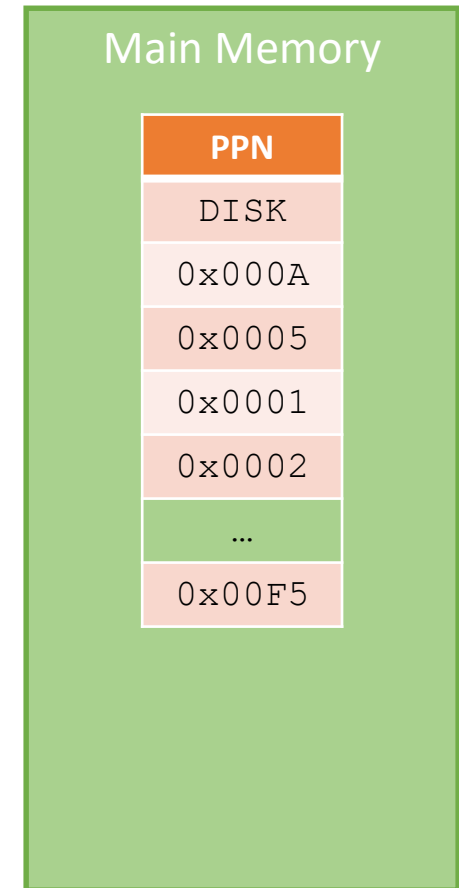
TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0001	0x000A

Physical Address [28 bits]



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TLB Example

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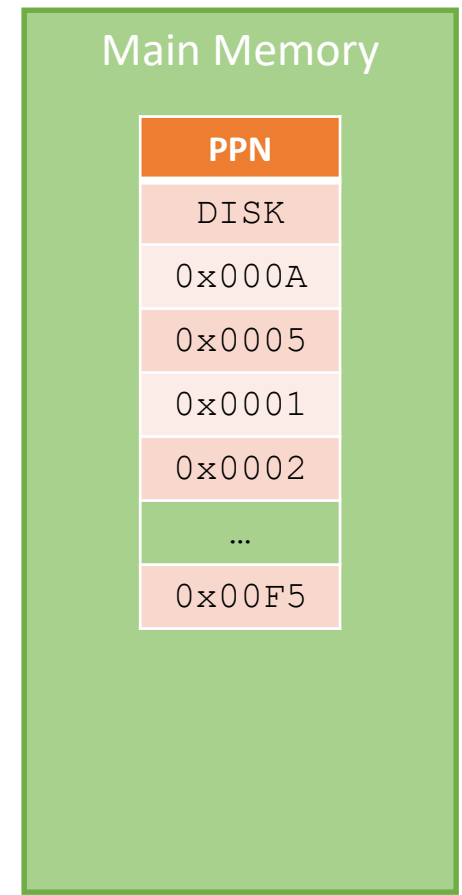
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0x0 0003	0x0001
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Physical Address [28 bits]



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28-bit Physical Address

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TLB Example

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Virtual Address [32 bit]



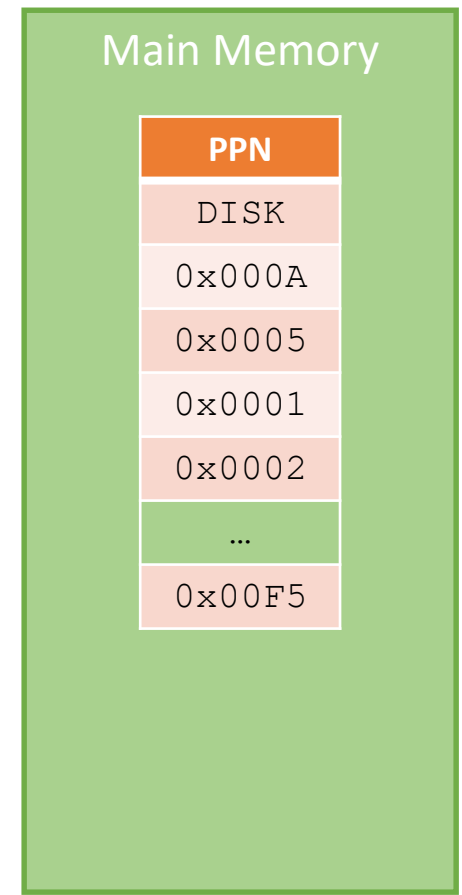
32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0001	0x000A

Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:
32-bit ISA, 156 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

Virtual Address [32 bit]



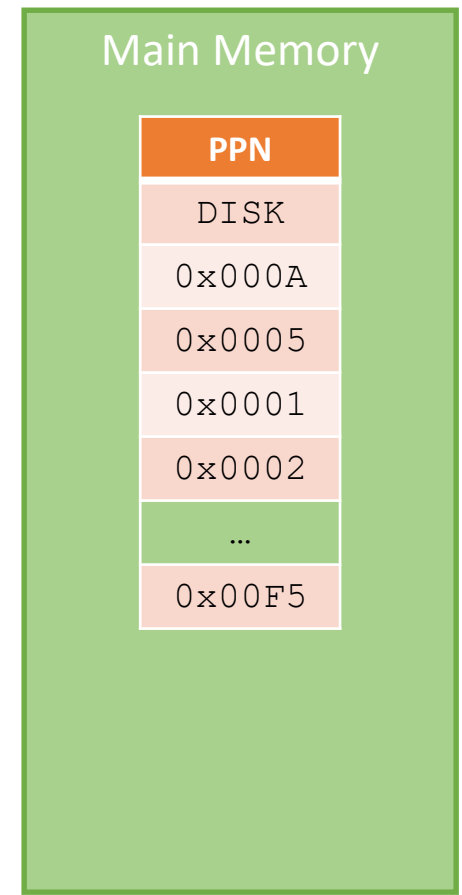
Tag	Physical Page #
0x0 0003	0x0001
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Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

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TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

Virtual Address [32 bit]



TLB [2-entries big]

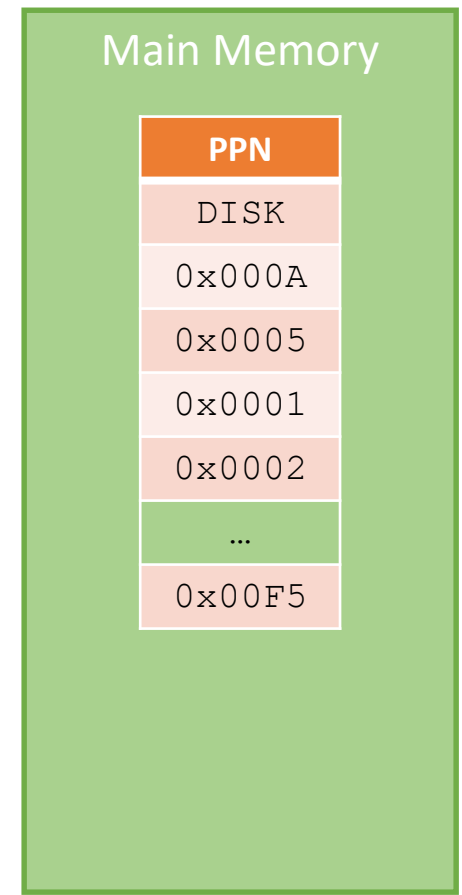
Tag	Physical Page #
0x0 0003	0x0001
0x0 0001	0x000A

Physical Address [28 bits]



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



TLB Example

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Computer Specs:

32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

Virtual Address [32 bit]



TLB [2-entries big]

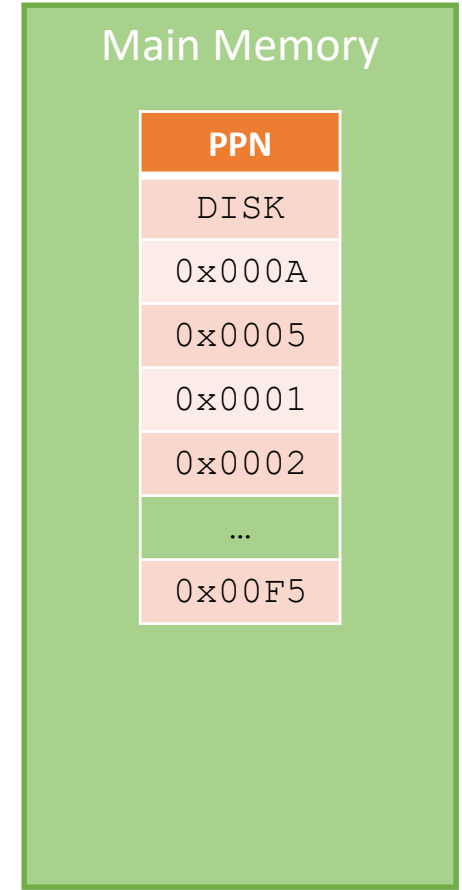
Tag	Physical Page #
0x0 0003	0x0001
0x0 0001	0x000A

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



Capacity Miss!

TLB Example

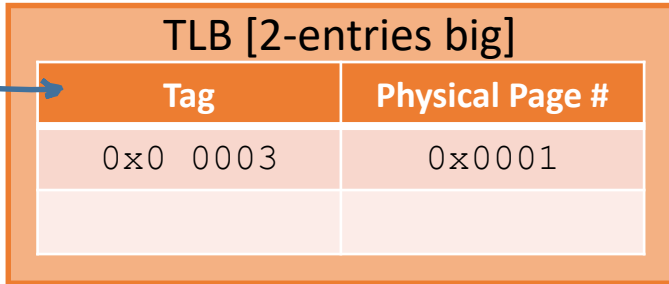
Quincy Flint

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VA: 0x00004 555

Virtual Address [32 bit]

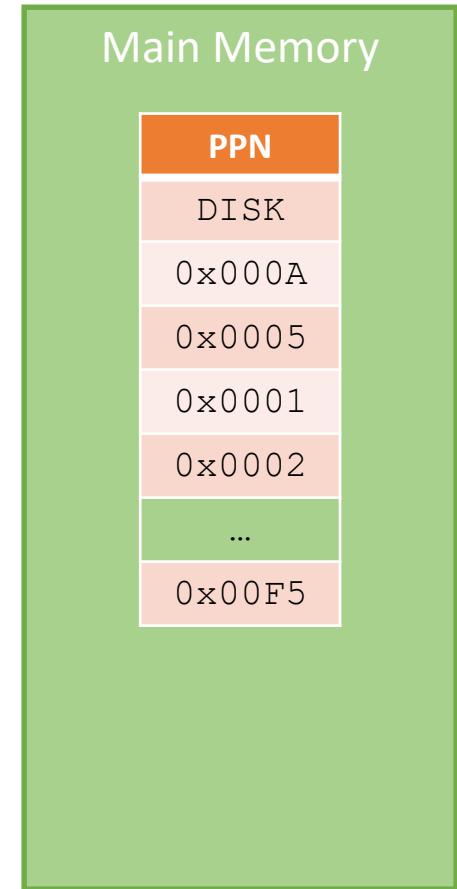


Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



Capacity Miss!

TLB Example

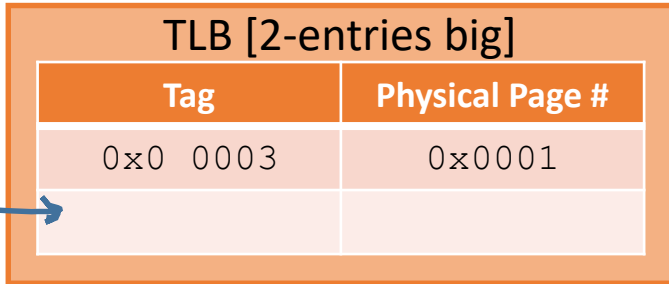
Quincy Flint

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VA: 0x00004 555

Virtual Address [32 bit]

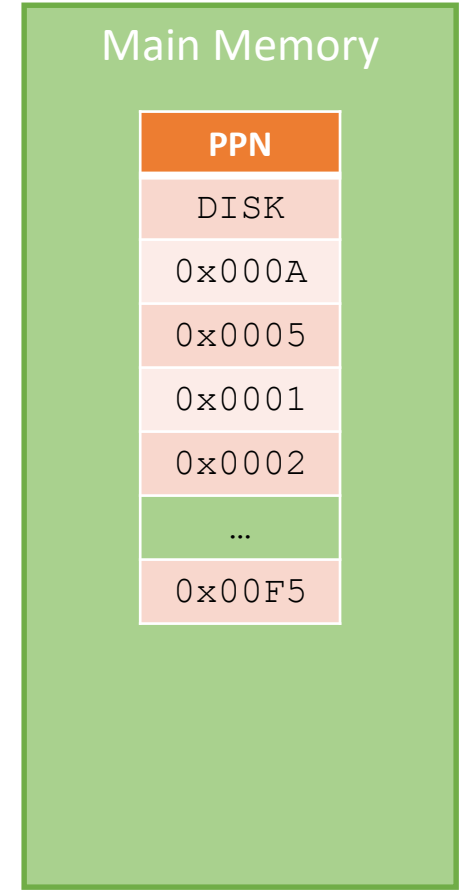


Physical Address [28 bits]



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28-bit Physical Address

12-bit Page Offset [Index]



Capacity Miss!

Quincy Flint

TLB Example

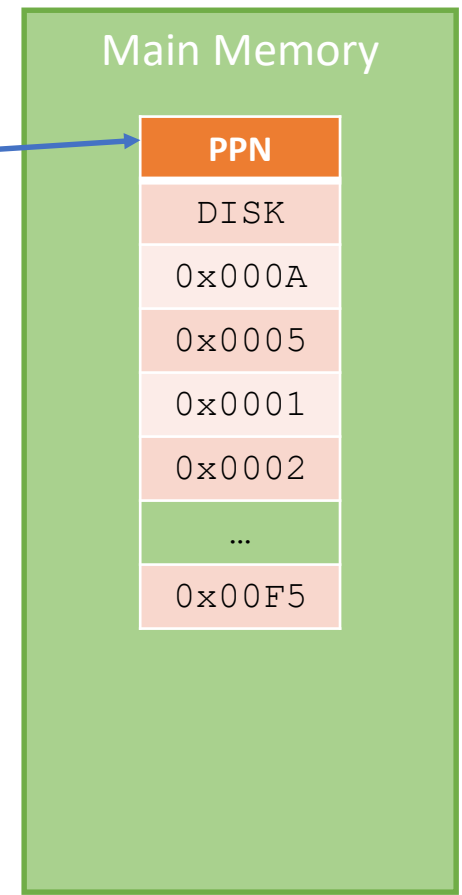
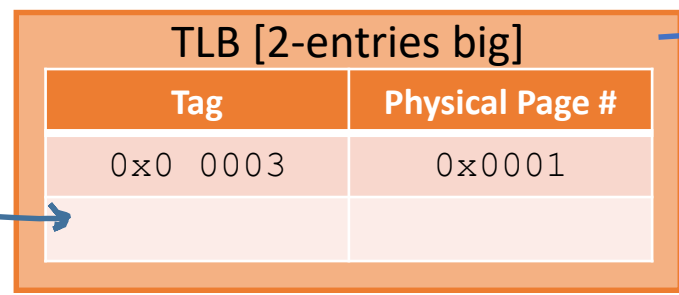
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32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

Virtual Address [32 bit]

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



Physical Address [28 bits]



Capacity Miss!

Quincy Flint

TLB Example

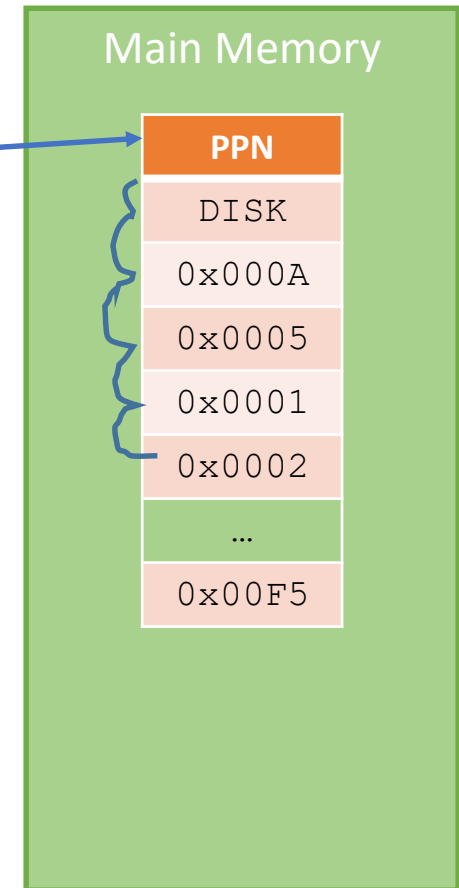
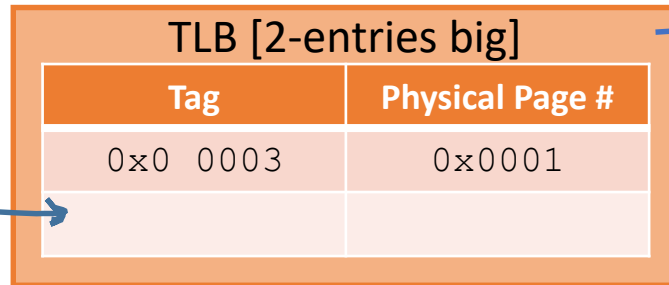
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32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

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Physical Address [28 bits]



Capacity Miss!

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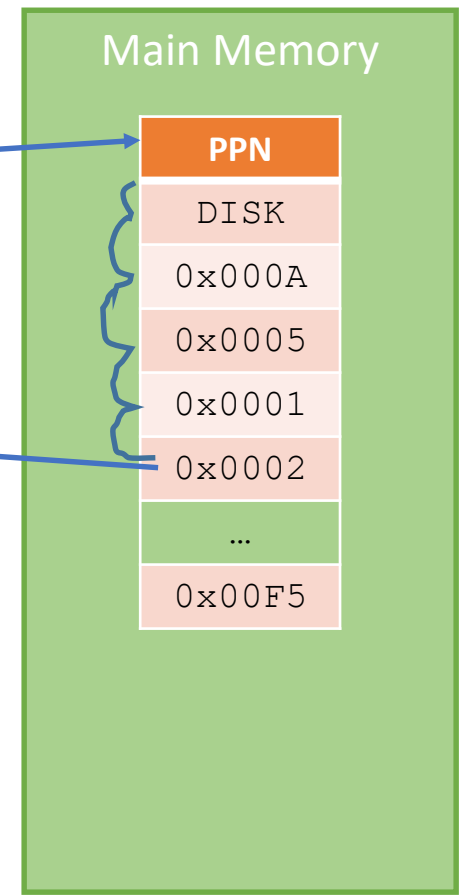
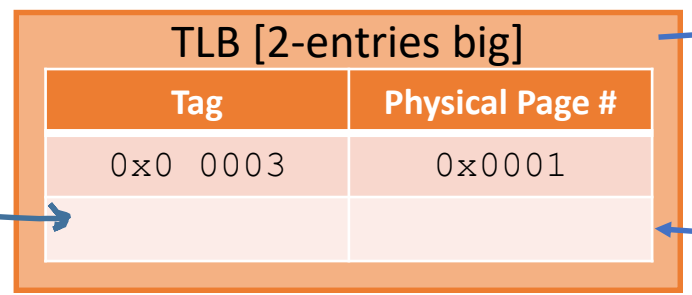
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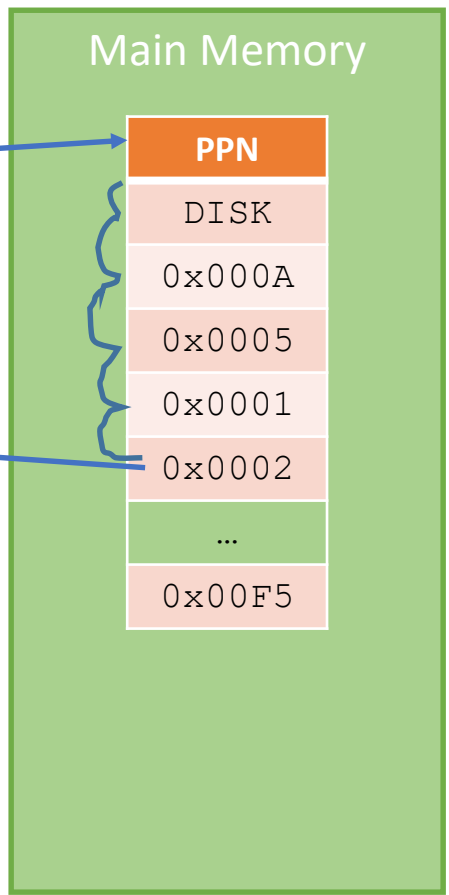
Virtual Address [32 bit]

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



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



Physical Address [28 bits]



Capacity Miss!

TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

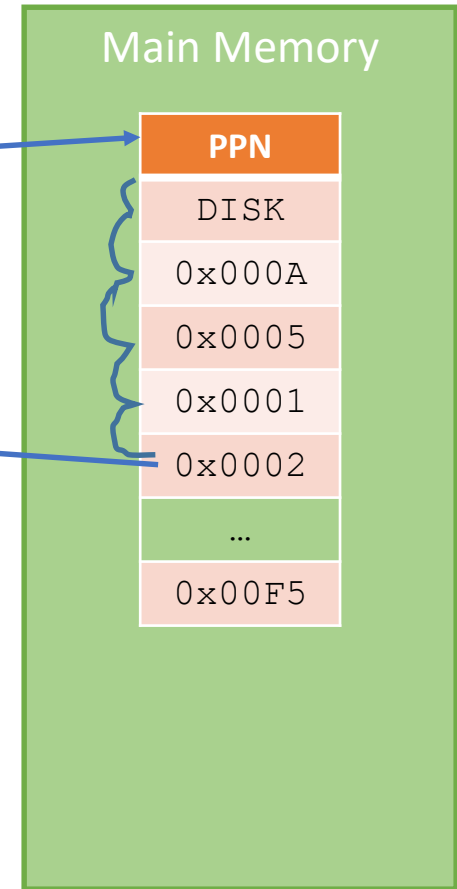
Virtual Address [32 bit]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

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



Physical Address [28 bits]



Capacity Miss!

TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

Virtual Address [32 bit]



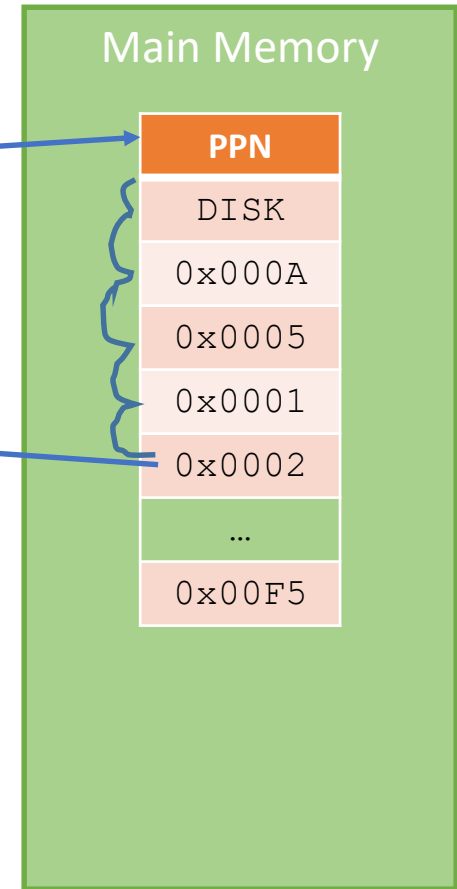
32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Capacity Miss!

TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00004 555

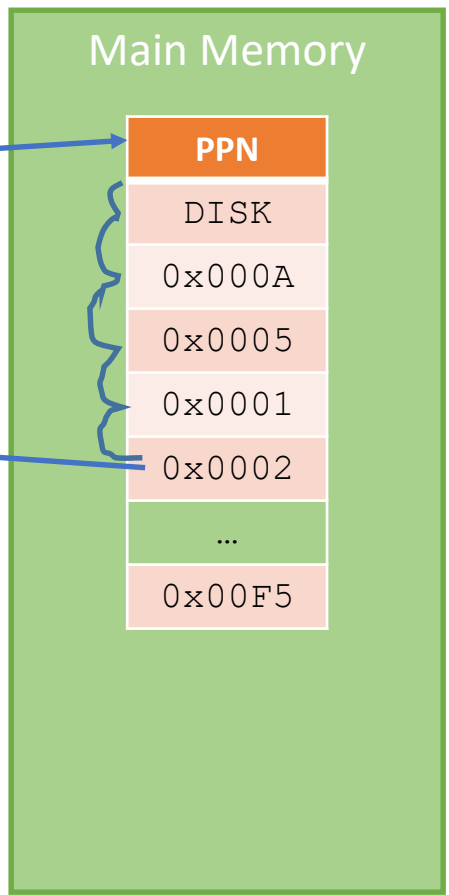
Virtual Address [32 bit]

32-bit Virtual Address
28-bit Physical Address

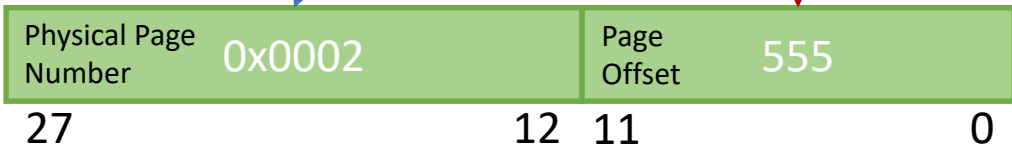
12-bit Page Offset [Index]



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



Physical Address [28 bits]



Capacity Miss!

TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

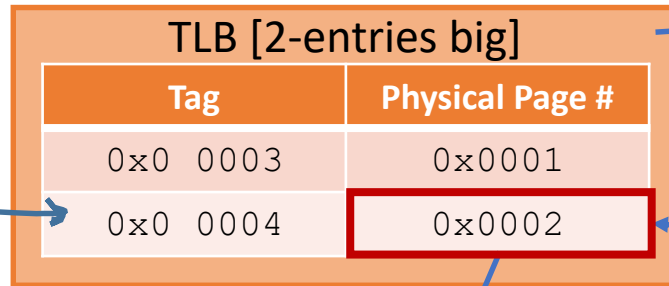


32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00004 555

Virtual Address [32 bit]

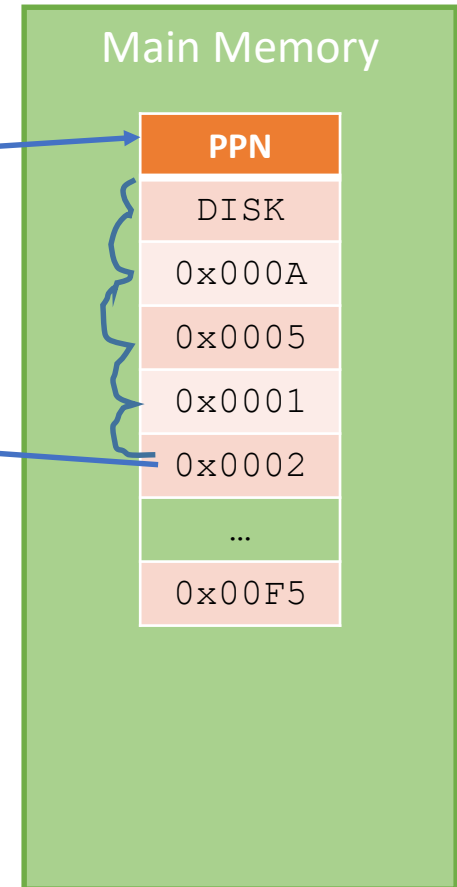


Physical Address [28 bits]



PA: 0x0002 555

Capacity Miss!



TLB Example

Quincy Flint

Computer Specs:
32-bit ISA, 156 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

Virtual Address [32 bit]



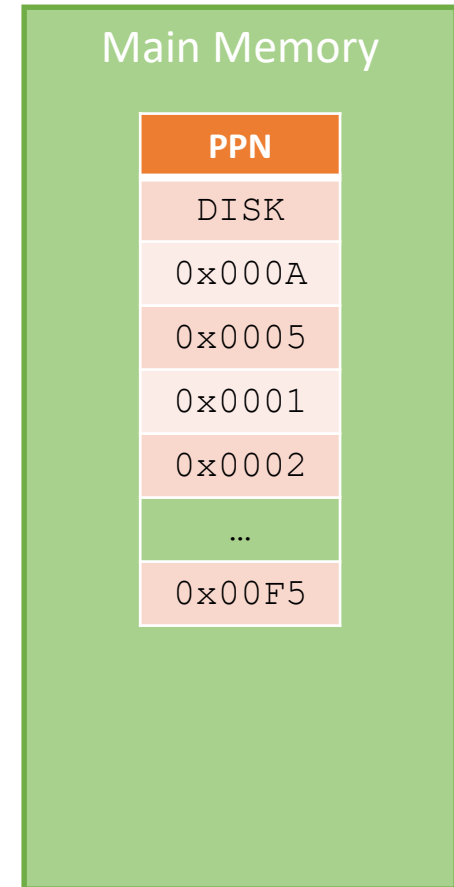
TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 156 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

Virtual Address [32 bit]



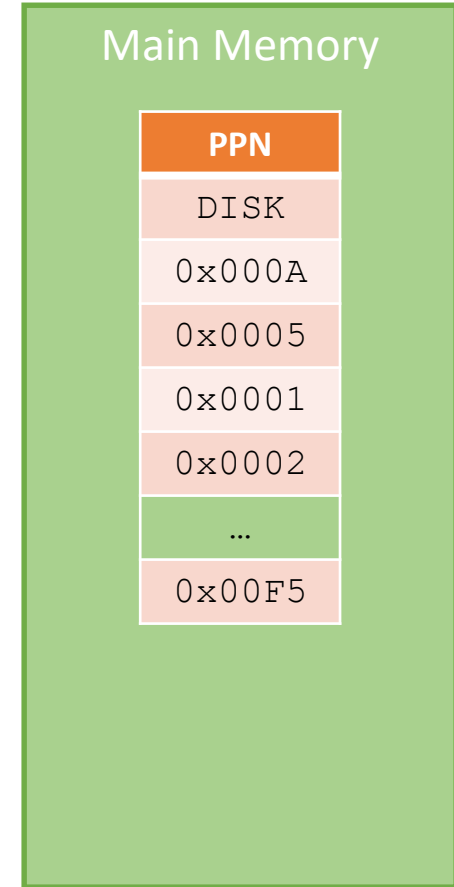
TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 156 MB RAM, 4 kB pages, 2-entry TLB



32-bit Virtual Address
28-bit Physical Address

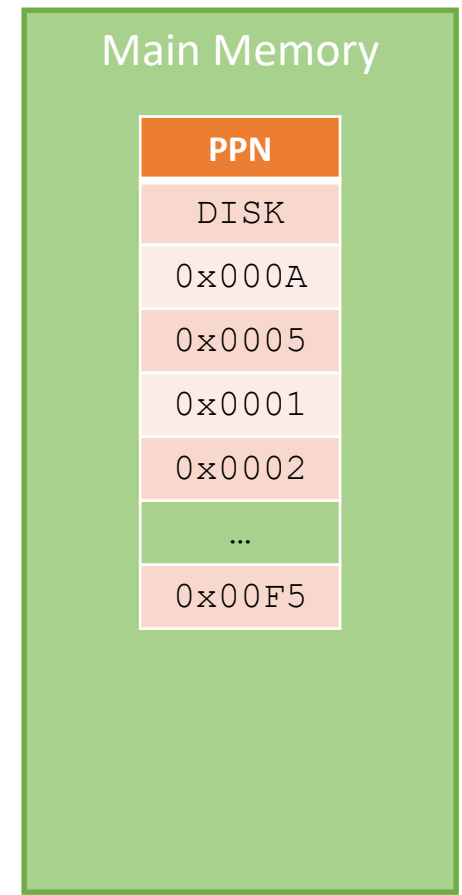
12-bit Page Offset [Index]

VA: 0x00003 099

Virtual Address [32 bit]



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



Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 156 MB of RAM, 4 kB pages, 2-entry TLB



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

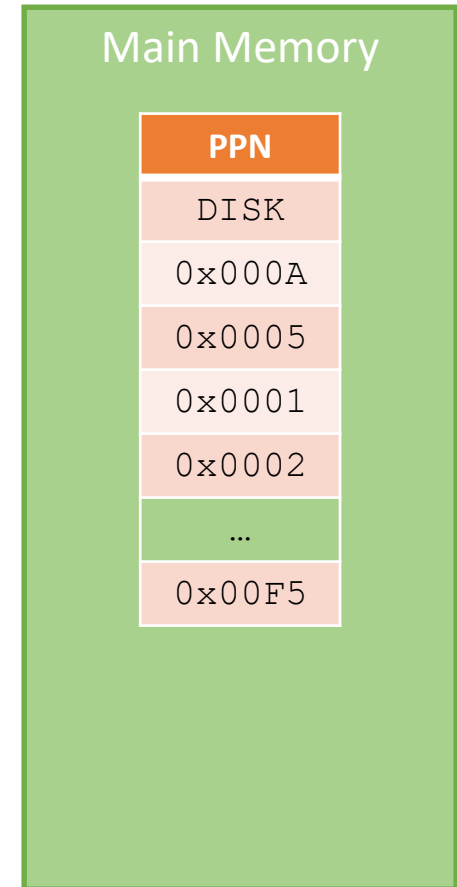
VA: 0x00003 099

Virtual Address [32 bit]



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

Physical Address [28 bits]



TLB Example

Quincy

Flint

Computer Specs:
32-bit VA, 156 MB of RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

Virtual Address [32 bit]



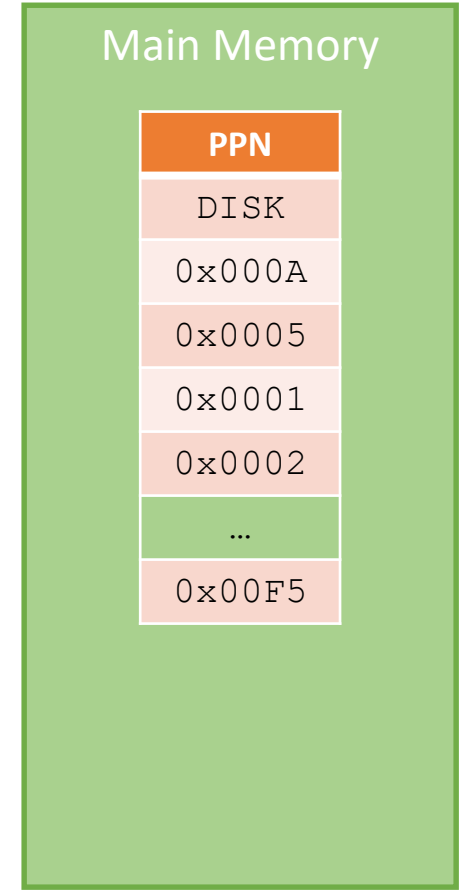
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Example

Quincy

Flint

Computer Specs:
32-bit VA, 156 MB of RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

Virtual Address [32 bit]



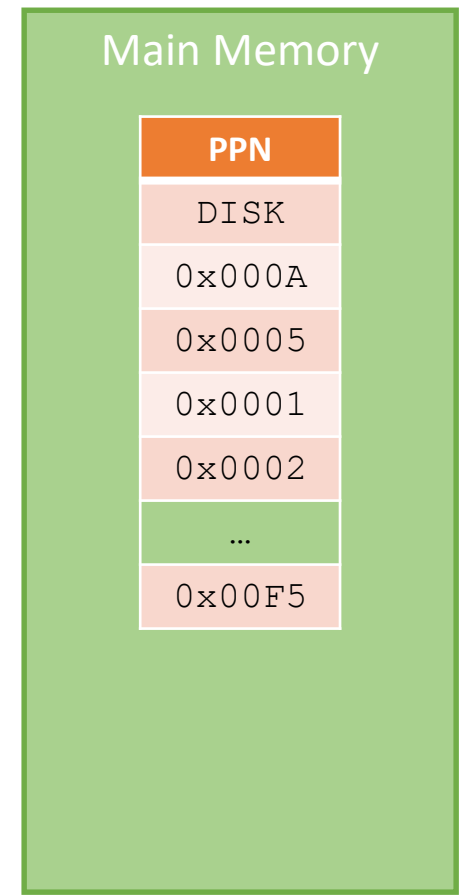
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Example

Quincy Flint

Computer Specs:
32-bit ISA, 156 MB of RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

Virtual Address [32 bit]

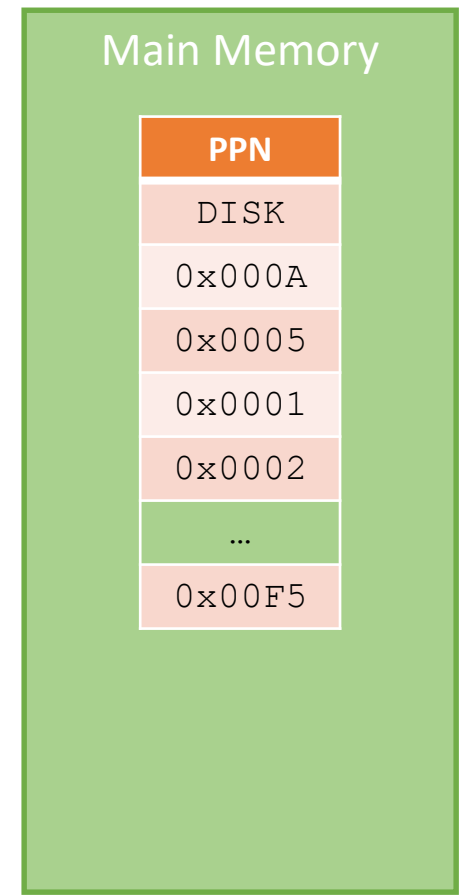


32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

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

Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

Virtual Address [32 bit]



TLB [2-entries big]

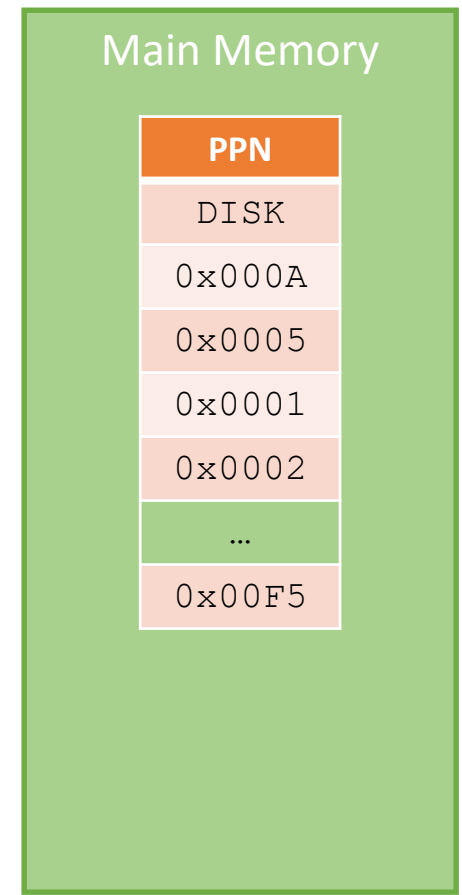
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

Virtual Address [32 bit]



TLB [2-entries big]

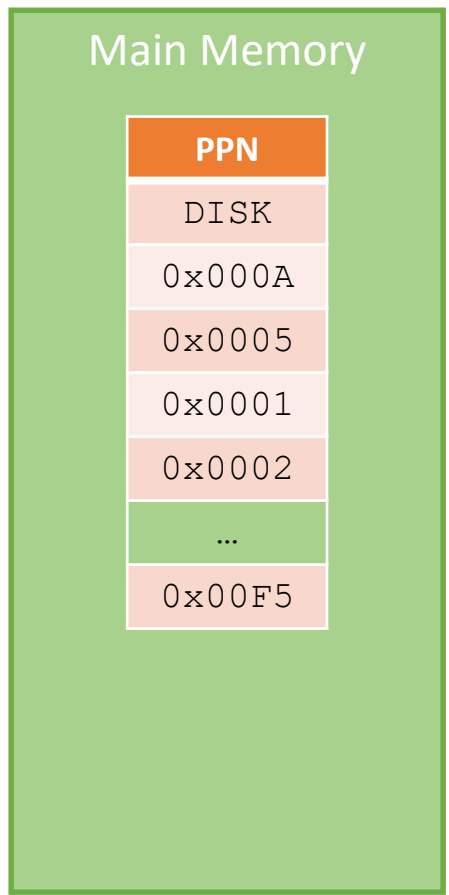
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Hit!

TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

Virtual Address [32 bit]



TLB [2-entries big]

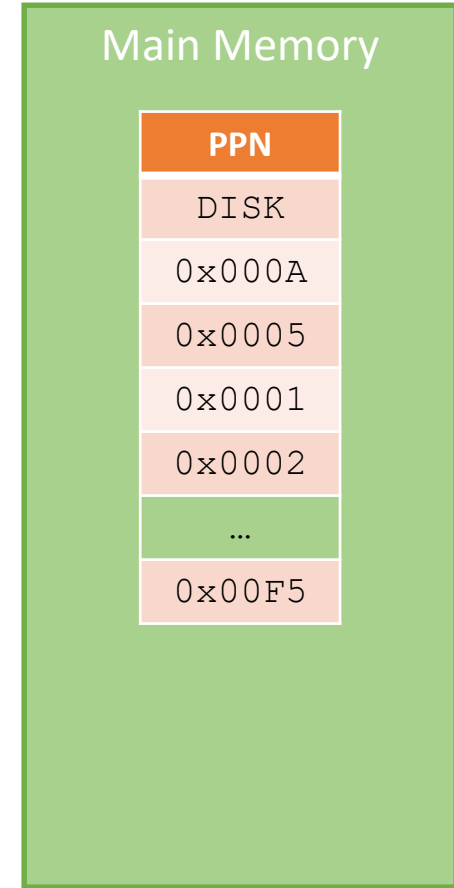
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Hit!

TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

Virtual Address [32 bit]



TLB [2-entries big]

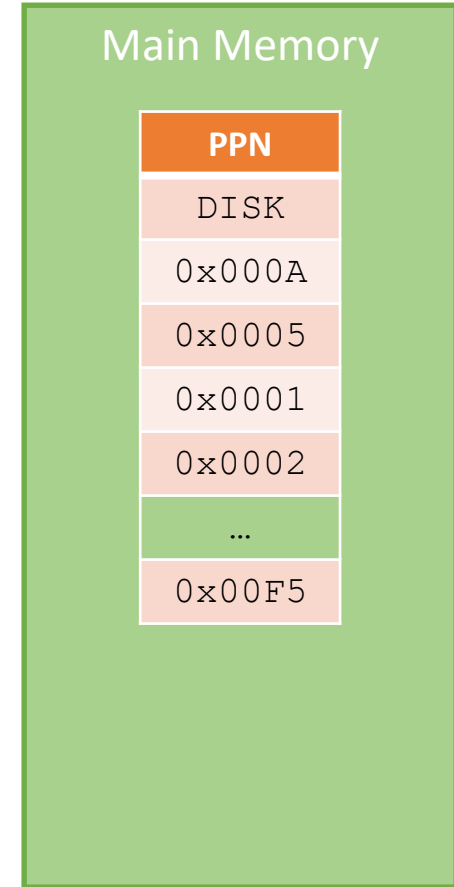
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Hit!

TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00003 099

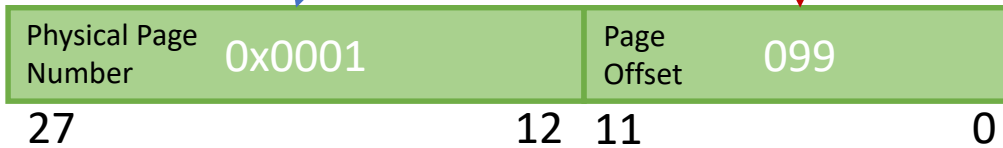
Virtual Address [32 bit]



TLB [2-entries big]

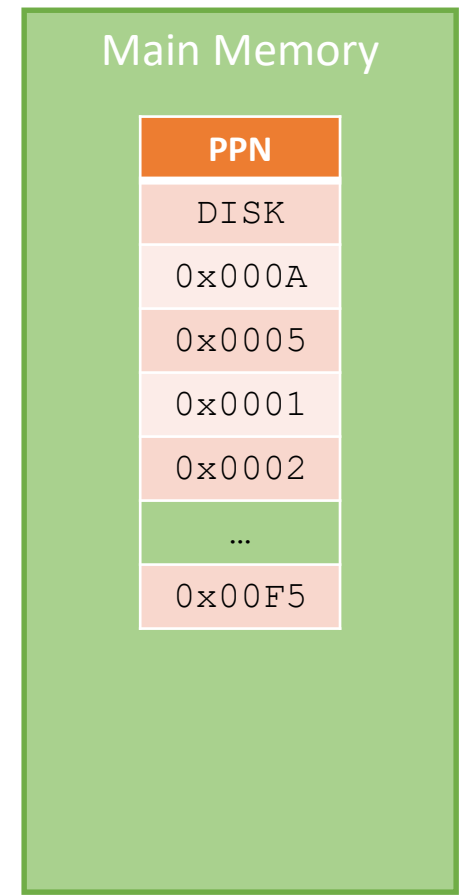
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Hit!

TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00003 099

Virtual Address [32 bit]



TLB [2-entries big]

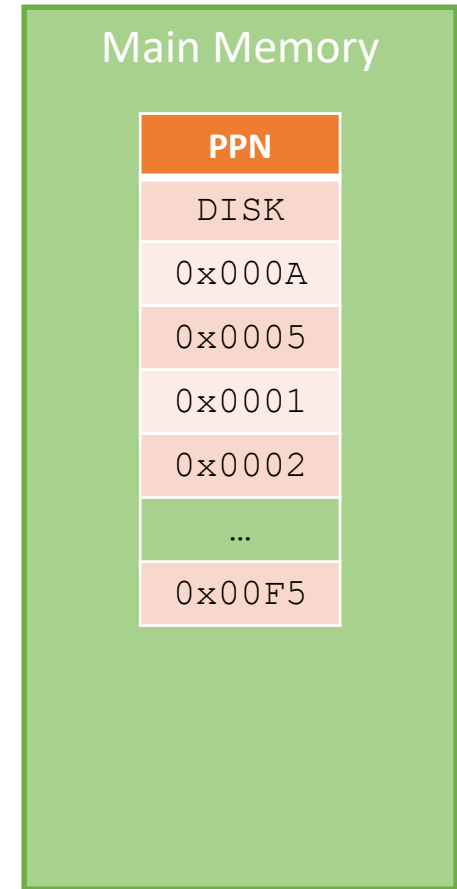
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



PA: 0x0001 099

TLB Hit!



TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 156 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00000 123

Virtual Address [32 bit]

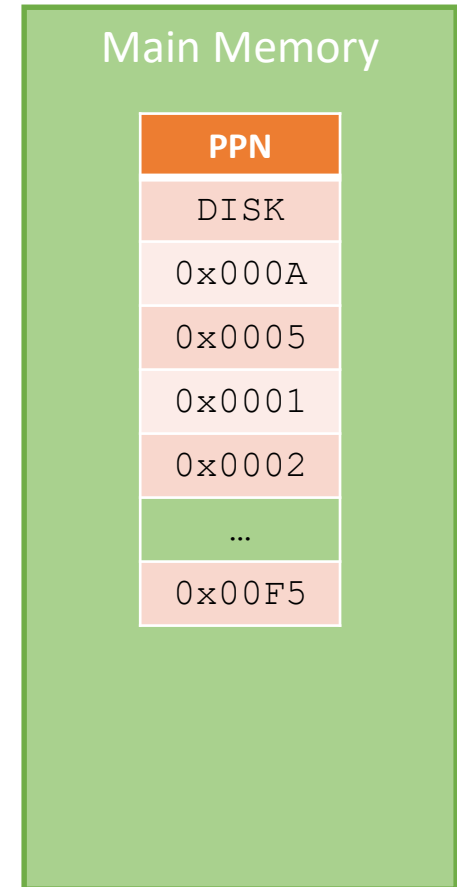


32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

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

Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 156 MB of RAM, 4 kB pages, 2-entry TLB



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00000 123

Virtual Address [32 bit]

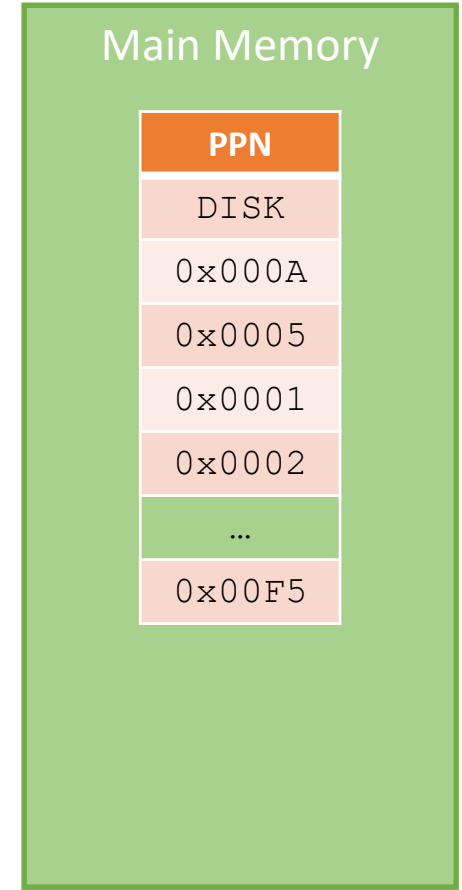


TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Q: What is the PA associated with this VA?

Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00000 123

Virtual Address [32 bit]



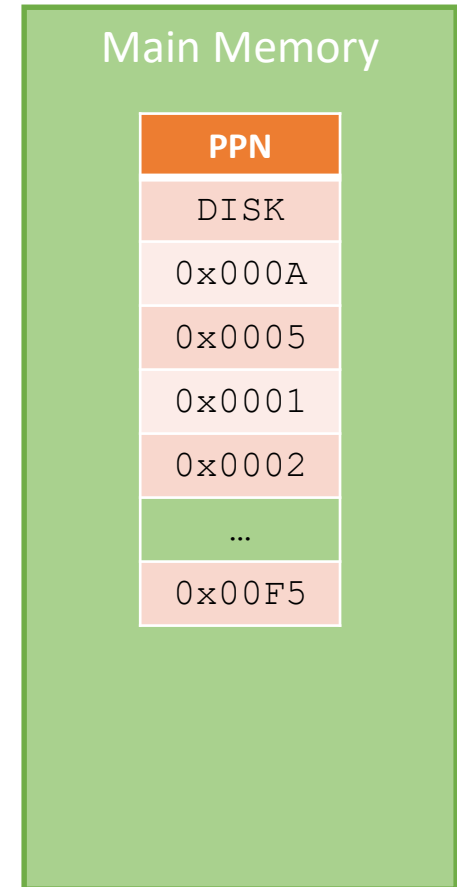
TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 156 MB RAM, 4 kB pages, 2-entry TLB



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

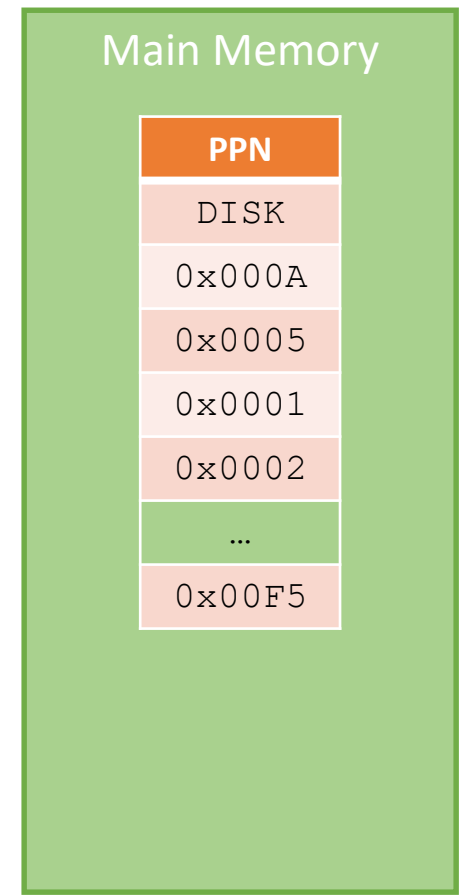
VA: 0x00000 123

Virtual Address [32 bit]



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

Physical Address [28 bits]



TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 156 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x00000 123

Virtual Address [32 bit]



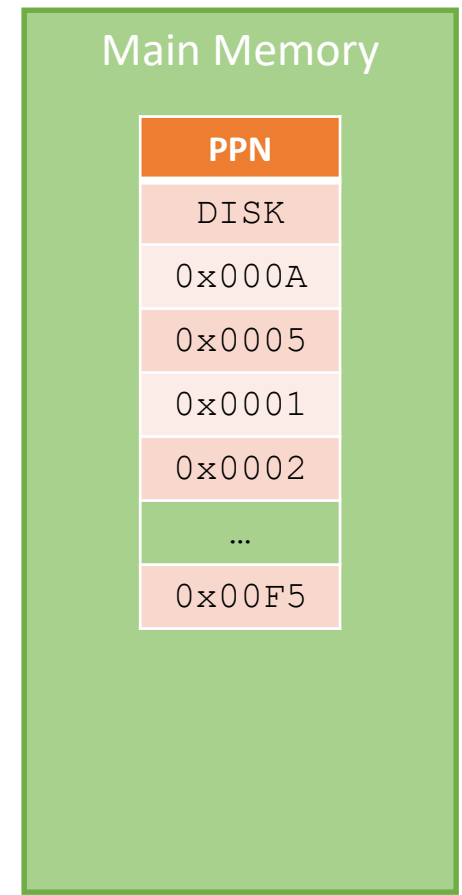
TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 156 MB of RAM, 4 kB pages, 2-entry TLB



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

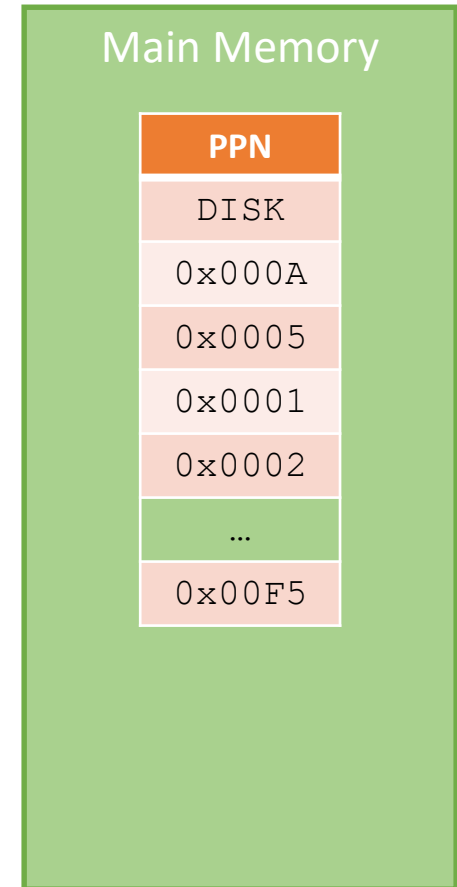
VA: 0x00000 123

Virtual Address [32 bit]



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

Physical Address [28 bits]



TLB Example

Quincy

Flint

Computer Specs:

32-bit VA, 156 MB of RAM, 4 kB pages, 2-entry TLB

VA: 0x0000 123

Virtual Address [32 bit]



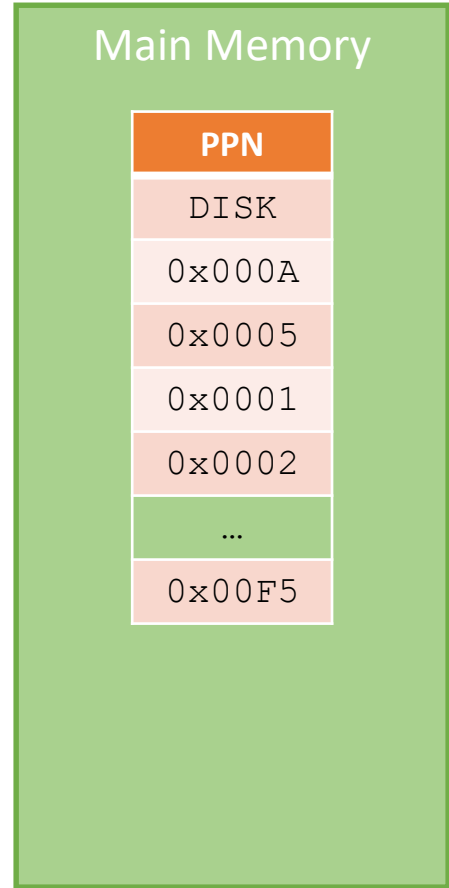
TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 156 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x0000 123

Virtual Address [32 bit]



TLB [2-entries big]

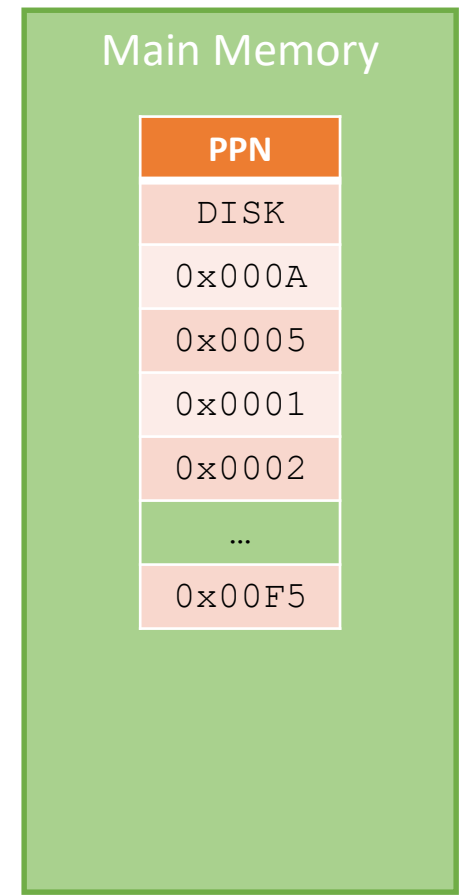
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x0000 123

Virtual Address [32 bit]



TLB [2-entries big]

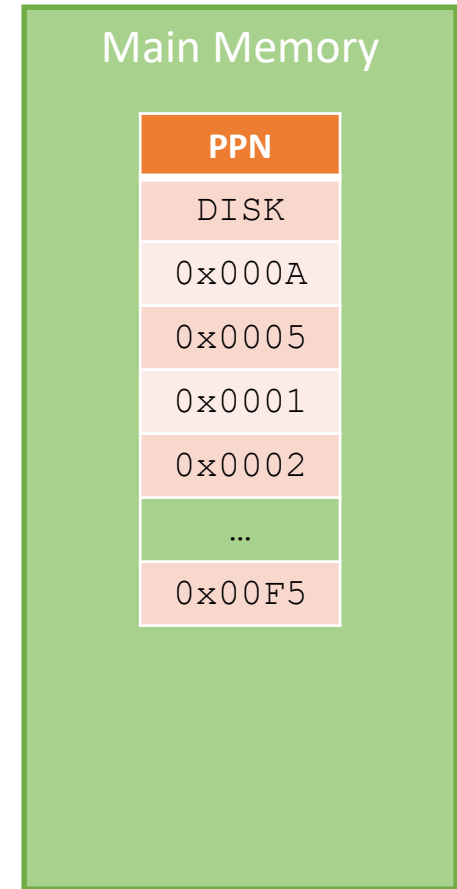
Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Miss!

TLB Example

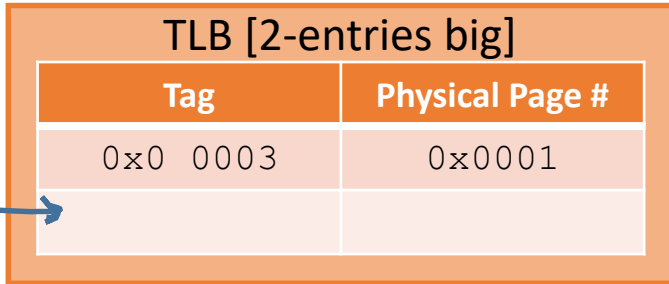
Quincy Flint

Computer Specs:

32-bit VA, 56 MB RAM, 4 kB pages, 2-entry TLB

VA: 0x0000 123

Virtual Address [32 bit]

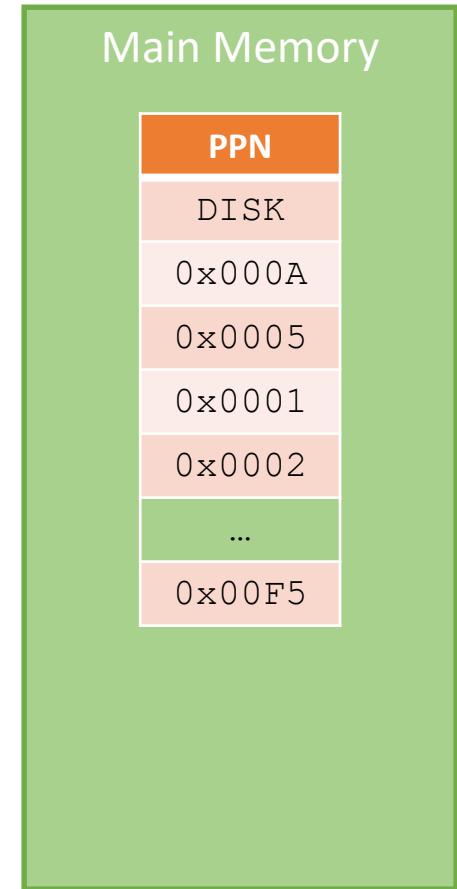


Physical Address [28 bits]



32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB Miss!

TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB of RAM, 4 kB pages, 2-entry TLB

VA: 0x0000 123

Virtual Address [32 bit]

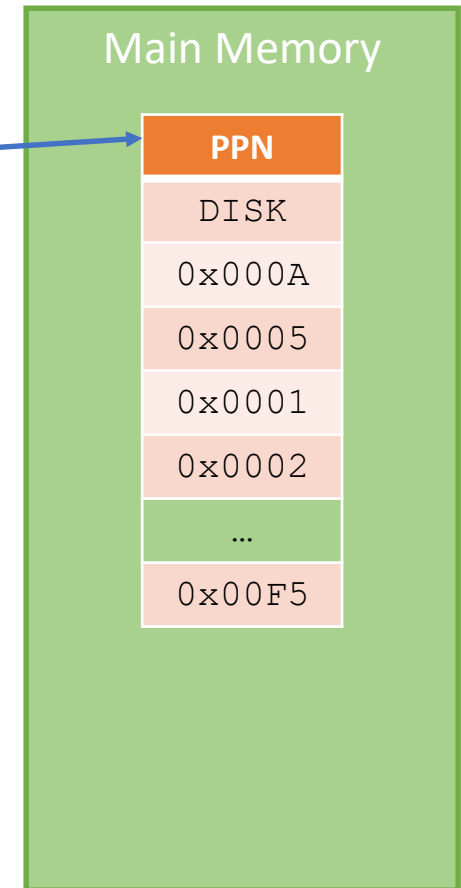


32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001



Physical Address [28 bits]



TLB Miss!

Quincy Flint

TLB Example

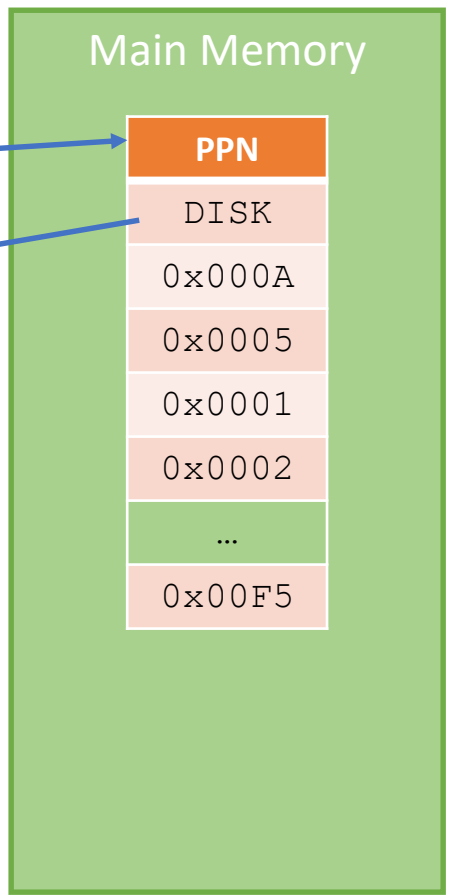
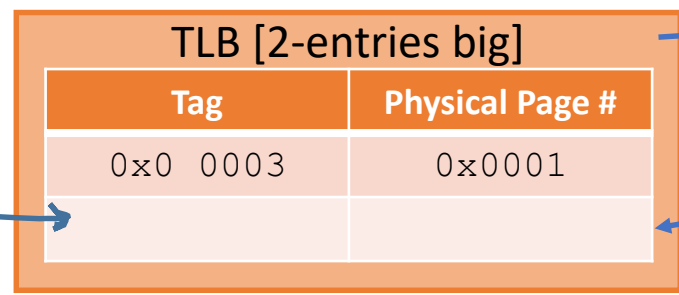
Computer Specs:
32-bit VA, 56 MB of RAM, 4 kB pages, 2-entry TLB

VA: 0x0000 123

Virtual Address [32 bit]

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



Physical Address [28 bits]



TLB Miss!

Quincy Flint

TLB Example

Computer Specs:
32-bit VA, 56 MB of RAM, 4 kB pages, 2-entry TLB

VA: 0x0000 123

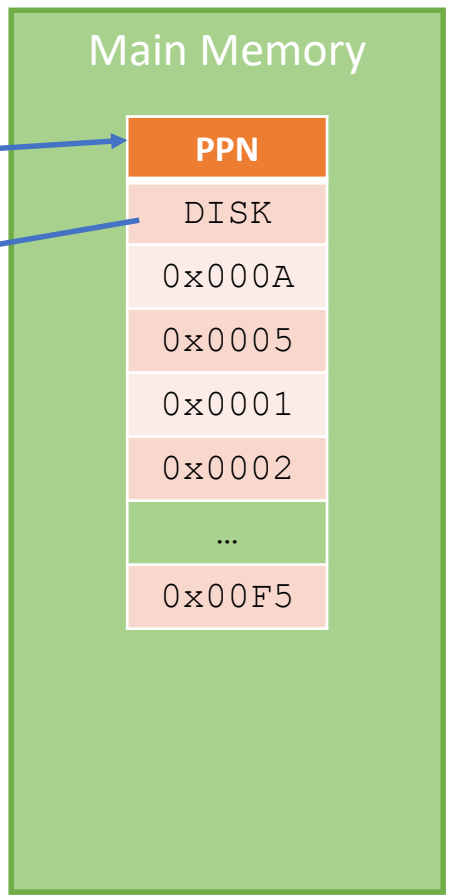
Virtual Address [32 bit]

32-bit Virtual Address
28-bit Physical Address

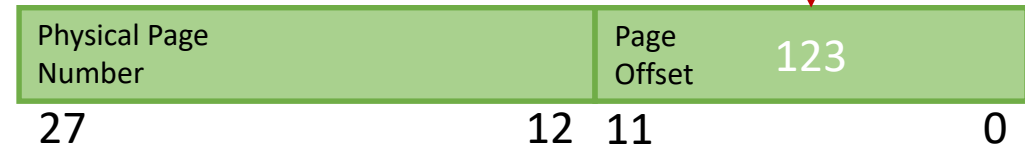
12-bit Page Offset [Index]



TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0000	DISK



Physical Address [28 bits]



TLB Miss!

TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 56 MB of RAM, 4 kB pages, 2-entry TLB

VA: 0x0000 123

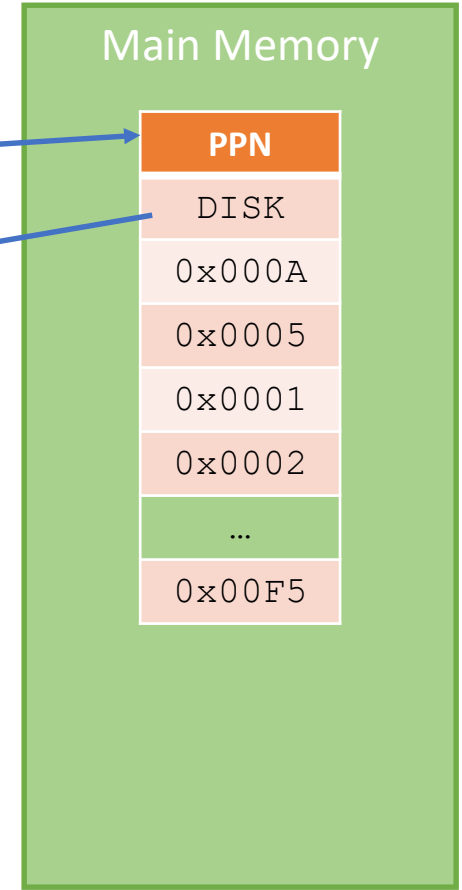
Virtual Address [32 bit]

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0000	DISK



Physical Address [28 bits]



TLB Miss!

TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB of RAM, 4 kB pages, 2-entry TLB

VA: 0x0000 123

Virtual Address [32 bit]



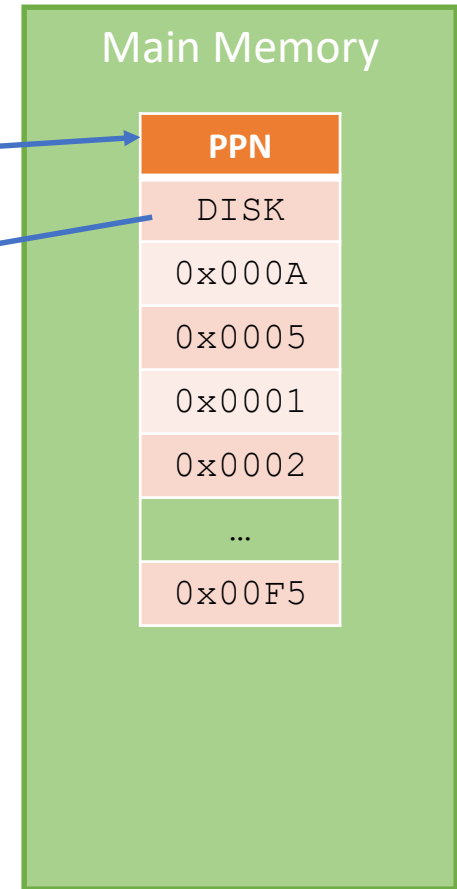
32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0000	DISK

Must bring into RAM from disk

Physical Address [28 bits]



TLB Miss!

TLB Example

Quincy Flint

Computer Specs:
32-bit VA, 56 MB of RAM, 4 kB pages, 2-entry TLB

VA: 0x0000 123

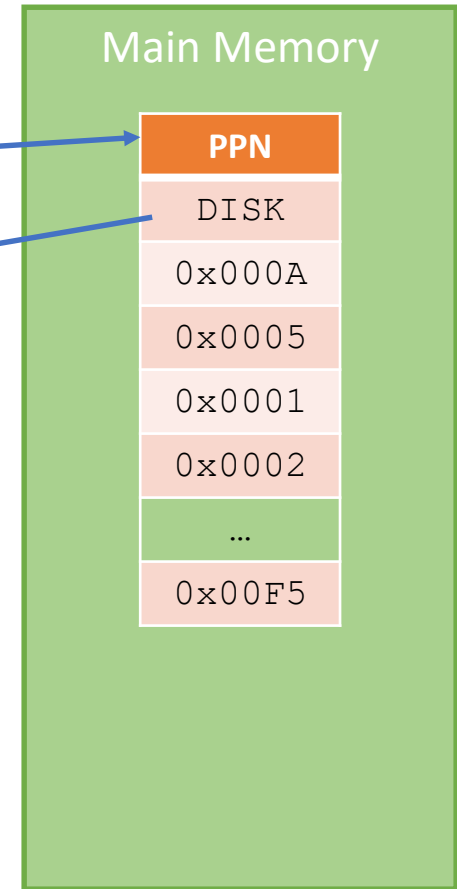
Virtual Address [32 bit]

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]



TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0000	DISK



Must bring into RAM from disk

Page Fault!

Physical Address [28 bits]



TLB Miss!

TLB Example

Quincy Flint

Computer Specs:

32-bit VA, 56 MB of RAM, 4 kB pages, 2-entry TLB



32-bit Virtual Address
28-bit Physical Address

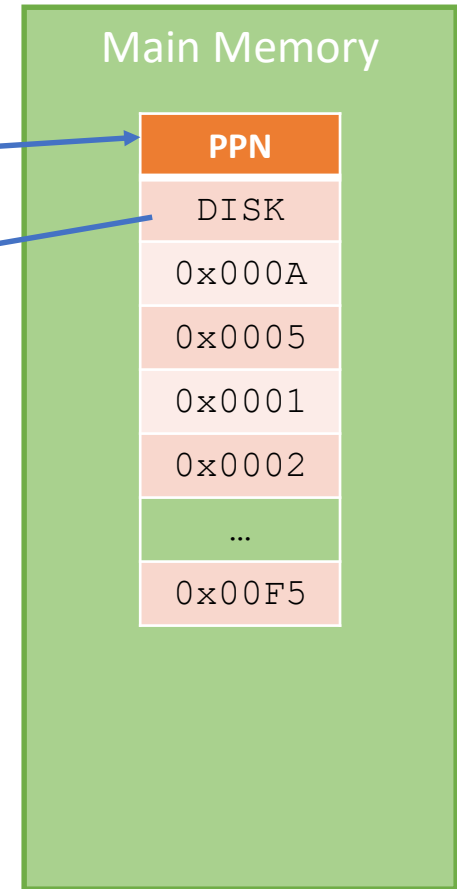
12-bit Page Offset [Index]

VA: 0x0000 123

Virtual Address [32 bit]



TLB [2-entries big]	
Tag	Physical Page #
0x0 0003	0x0001
0x0 0000	DISK



Must bring into RAM from disk

Page Fault!

Physical Address [28 bits]



PA: Need more info

TLB Miss!

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