Final Exam Prep Session
Virtual Memory

15-213: Introduction to Computer Systems
May 8, 2013

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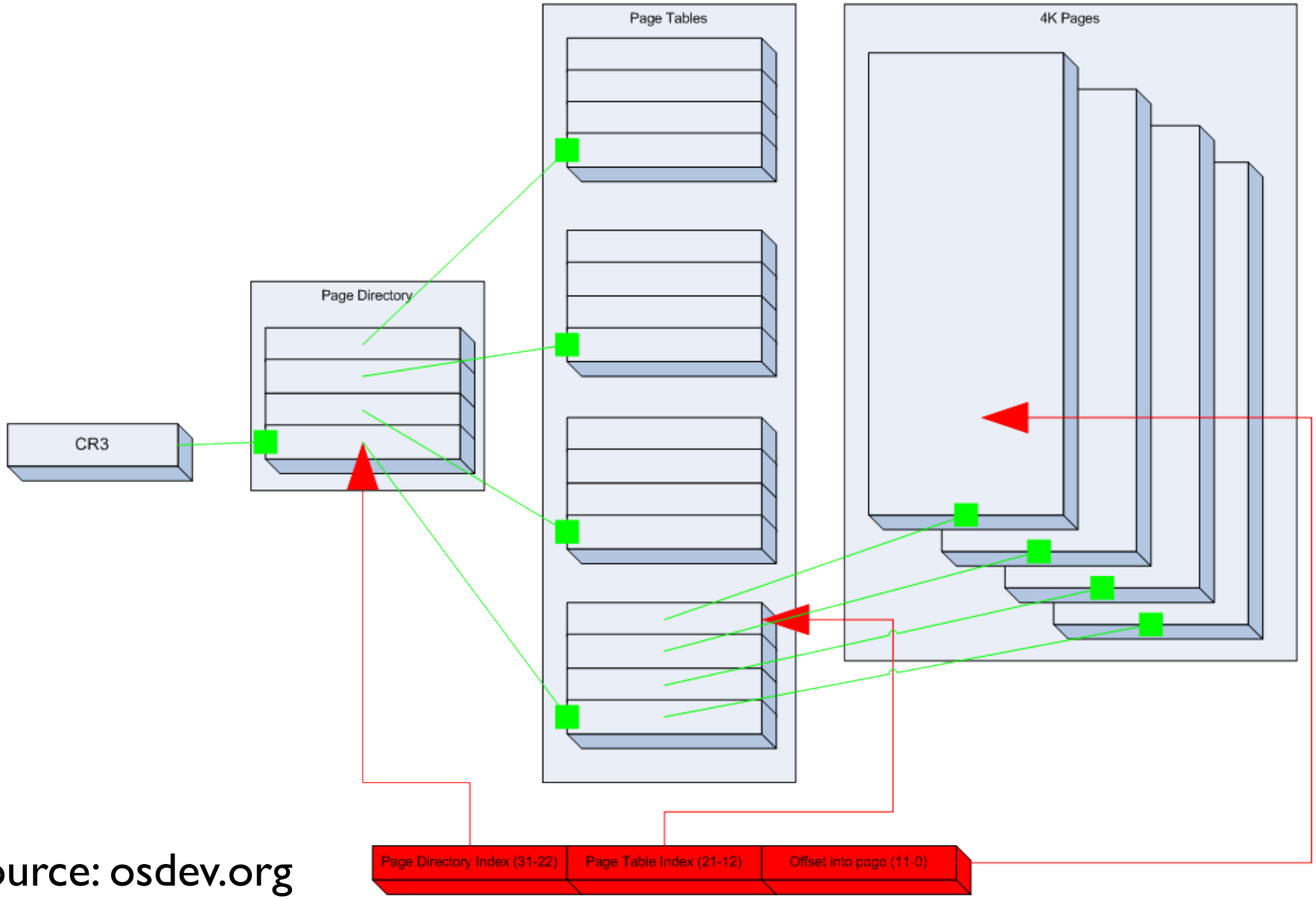
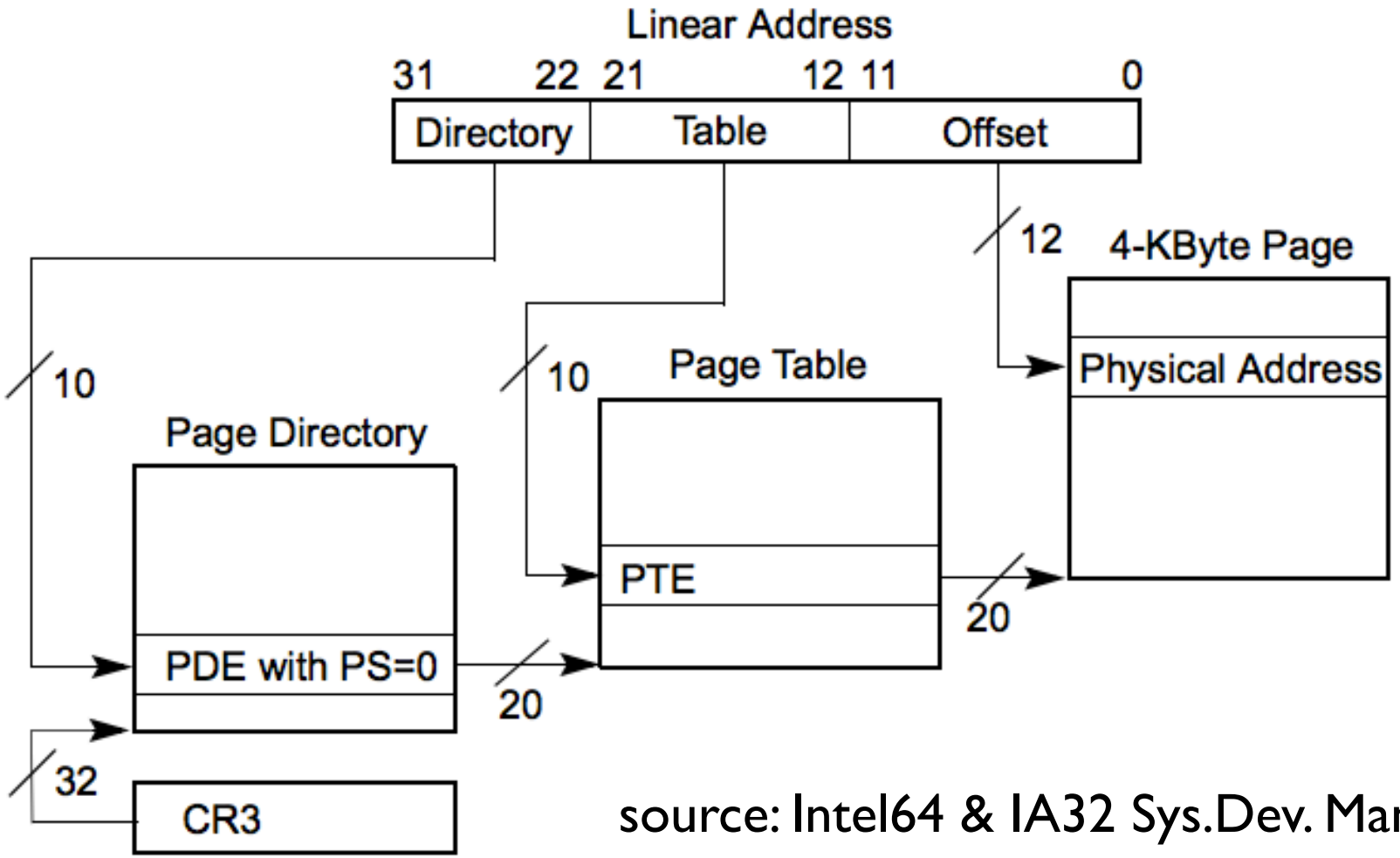
Section C

IA32 Two-Level Page Tables



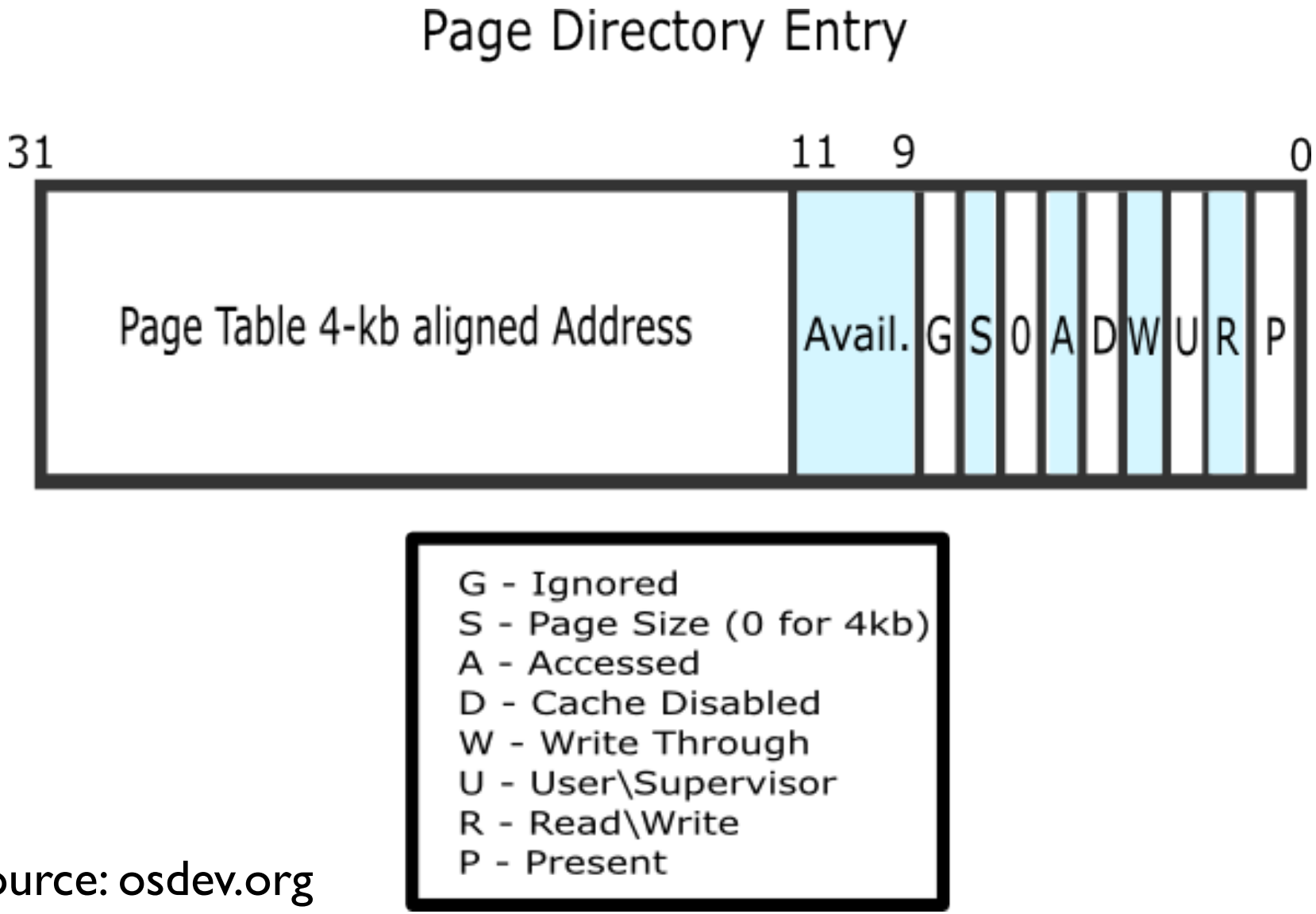
source: osdev.org

IA32 Two-Level Page Tables



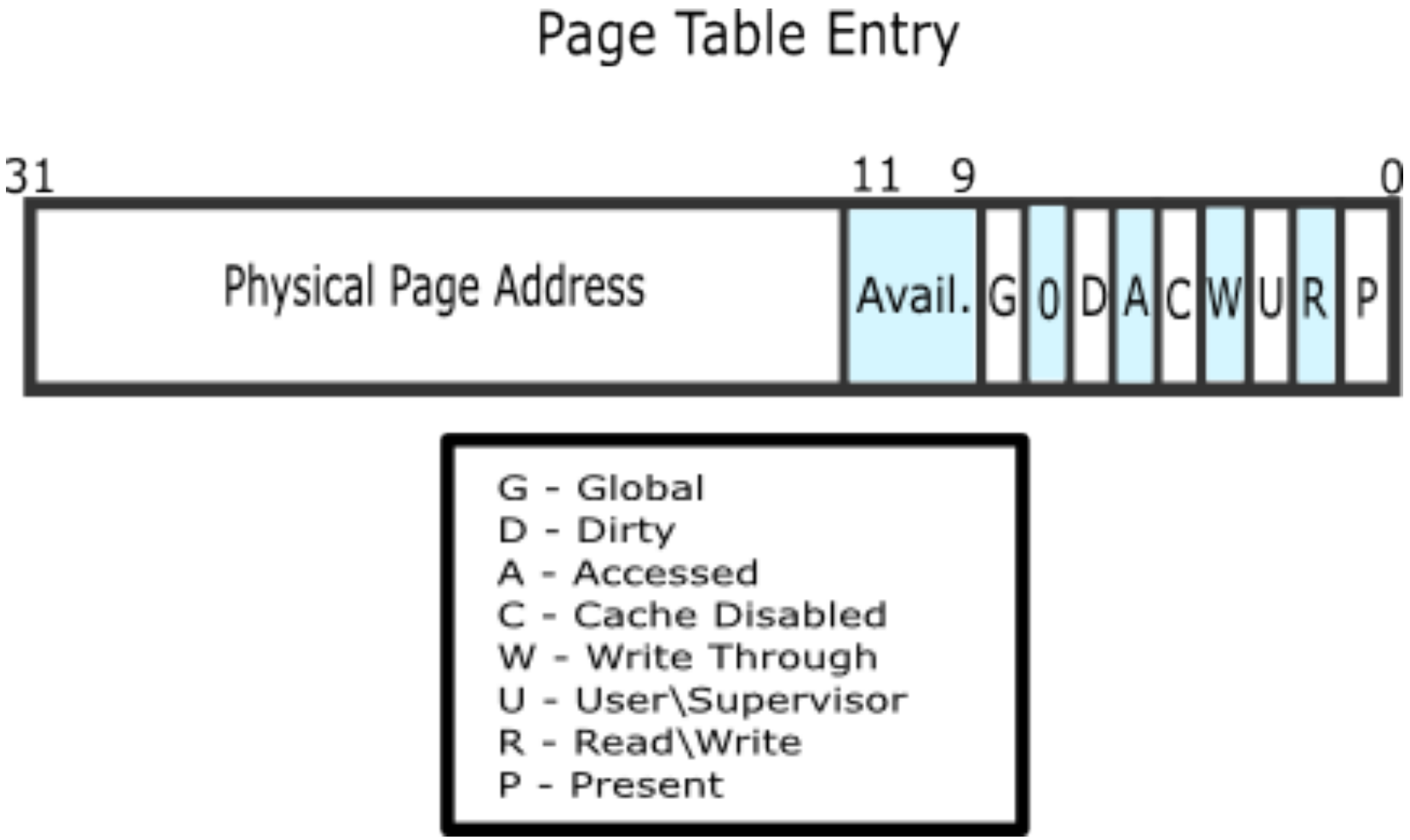
source: Intel64 & IA32 Sys.Dev. Manual
Figure 4-2

IA32 Two-Level Page Tables: PDE Flags



source: osdev.org

IA32 Two-Level Page Tables: PTE Flags



source: osdev.org

TLB Lookup

VA = 0x9fd28c10 = VPN:VPO = 9fd28c10

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
1	0	0	1	1	1	1	1	1	1	0	1	0	0	1	0
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
1	0	0	1	1	1	1	1	1	1	0	1	0	0	1	0
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0

VA = 0x9fd28c10 = TLBT:TLBI:VPO
TLBT = 10 0111 1111 0100 1010 = 0x27f4a
TLBI = 00 = 0x0

MISS

Page Directory Entry Lookup

VA = 0x9fd28c10 = PDI|PTI|VPO

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
1	0	0	1	1	1	1	1	1	1	0	1	0	0	1	0
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0

phaddr(PDE) = base(PD) + offset(PDE)

= base(PD) + PDI*sizeof(PDE)

= base(PD) + PDI*4

= base(PD) + PDI<<2

PDI = 10 0111 1111 = 27f

offset(PDE) = PDI<<2 = 1001 1111 1100 = 9fc

phaddr(PDE) = 0045d000 + 9fc = 0045d9fc (1b)

PDE contents

```
phaddr(PDE) = 0045d9fc
contents(PDE) = 0df2a237 → present bit set
base(PT) = contents(PDE) & ~fff = 0df2a000
```

Page Table Entry Lookup

VA = 0x9fd28c10 = PDI|PTI|VPO

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
1	0	0	1	1	1	1	1	1	1	0	1	0	0	1	0
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0

phaddr(PTE) = base(PT) + offset(PTE)

= base(PT) + PTI*sizeof(PTE)

= base(PT) + PTI*4

= base(PT) + PTI<<2

PTI = 01 0010 1000 = …

offset(PTE) = PTI<<2 = 0100 1010 0000 = 4a0

phaddr(PTE) = 0df2a000 + 4a0 = 0df2a4a0 (1c)

PTE contents

```
phaddr(PTE) = 0df2a4a0
contents(PTE) = 00324236 → present bit NOT set
```

Again…

TLB Lookup

VA = 0x0d4182c0 = VPN:VPO = 0d418:2c0

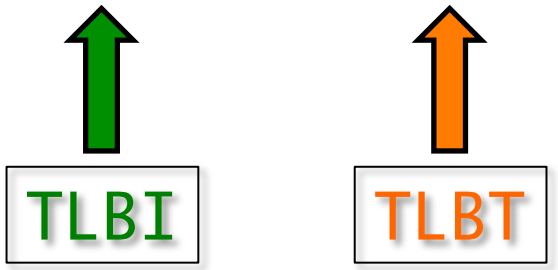
31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
0	0	0	0	1	1	0	1	0	1	0	0	0	0	0	1
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0												

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
0	0	0	0	1	1	0	1	0	1	0	0	0	0	0	1
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0												

VA = 0x0d4182c0 = TLBT:TLBI:VPO
TLBT = 00 0011 0101 0000 0110 = 0x03506
TLBI = 00 = 0x0

TLB Contents

Index	Tag	PPN	Valid
0x0	0x03506	0x98f8a	1 (YES)



PA = PPN:PPO = PPN:VPO = 0x98f8a2c0

Again…

TLB Lookup

VA = 0x0a32fcd0 = VPN:VPO = 0a32fcd0

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
0	0	0	0	1	0	1	0	0	0	1	1	0	0	1	0
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	1	1												

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
0	0	0	0	1	0	1	0	0	0	1	1	0	0	1	0
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	1	1												

VA = 0x0a32fcd0 = TLBT:TLBI:VPO
TLBT = 00 0010 1000 1100 1011 = 0x028cb
TLBI = 11 = 0x3

MISS

Page Directory Entry Lookup

VA = 0x0a32fcd0 = PDI|PTI|VPO

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
0	0	0	0	1	0	1	0	0	0	1	1	0	0	1	0
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	1	1												

phaddr(PDE) = base(PD) + offset(PDE)

= base(PD) + PDI*sizeof(PDE)

= base(PD) + PDI*4

= base(PD) + PDI<<2

PDI = 0000101000 = …

offset(PDE) = PDI<<2 = 0000 1010 0000= 0a0

phaddr(PDE) = 0045d000 + 0a0 = 0045d0a0 (3b)

PDE contents

```
phaddr(PDE) = 0045d0a0
contents(PDE) = 000c3297→ present bit set
base(PT) = contents(PDE) & ~fff = 000c3000
```

Page Table Entry Lookup

VA = 0x0a32fcd0 = PDI|PTI|VPO

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
0	0	0	0	1	0	1	0	0	0	1	1	0	0	1	0
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	1	1												

phaddr(PTE) = base(PT) + offset(PTE)

= base(PT) + PTI*sizeof(PTE)

= base(PT) + PTI*4

= base(PT) + PTI<<2

PTI = 1100101111 = …

offset(PTE) = PTI<<2 = 1100 1011 1100 = cbc

phaddr(PTE) = 000c3000 + cbc = 000c3cbc (3c)

PTE contents

```
phaddr(PTE) = 000c3cbc
contents(PTE) = 34abd237 → present bit set
contents(PTE) = PPN:flags = 34abd:237

PPN = 34abd
PPO = VPO = cd0

PA = PPN:PPO = 34abdcd0   (3d)
```

SUCCESS

PTE contents

phaddr(PTE) = 000c3cbc
contents(PTE) = 34abd237 → present bit **set**
contents(PTE) = PPN:flags = 34abd:237

base(P) = contents(PTE) & ~fff = PPN:000

PA = base(P) + offset = 34abd000 + cd0
PA = 34abdcd0

What are you trying to tell me?

- That I can dodge bullets?

When you are ready

- You won't have to…