Operating Systems

Lecture 12: Paging + TLB

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CS stories

https://www.youtube.com/watch?v=kTn56jJW4zY

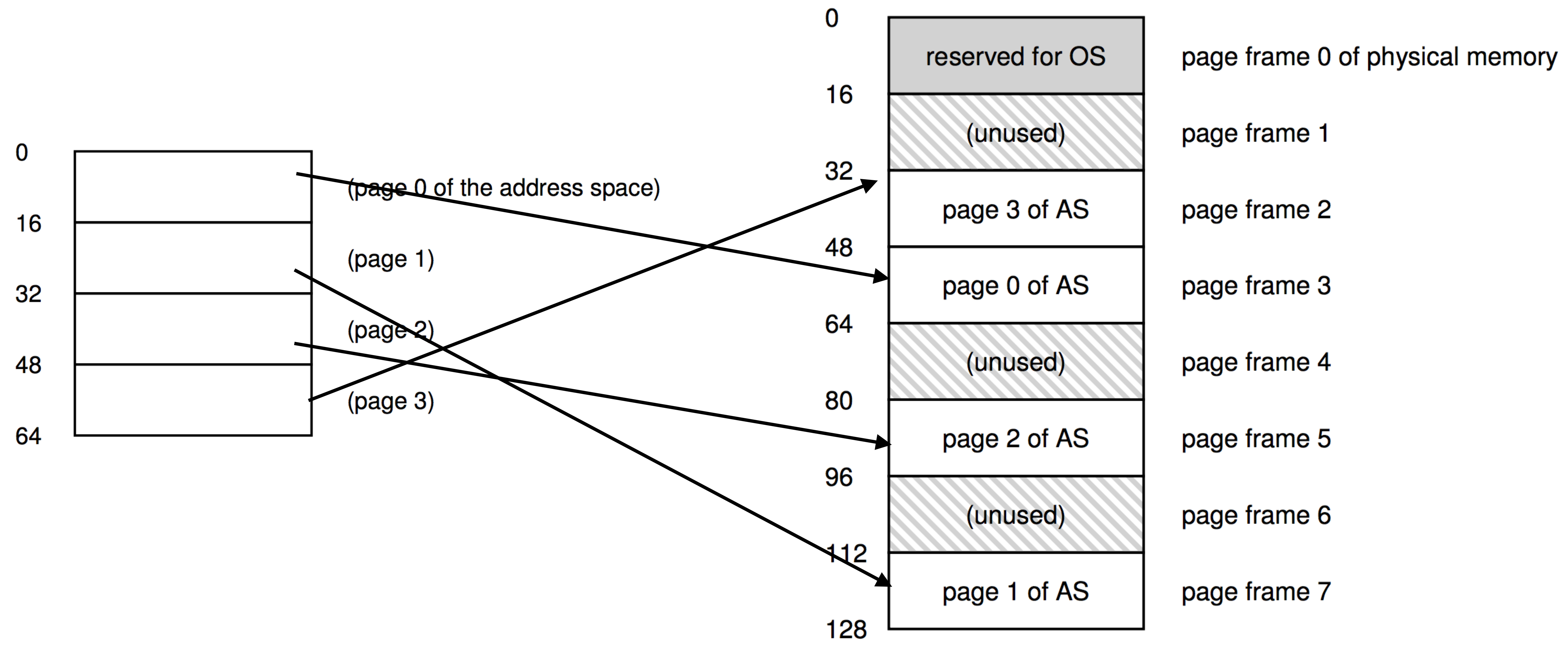
Revision

1. Segmentation
    1. Registers containing:
        1. Start VA
        2. Bounds
        3. …. (think Stack)
        4. … (save memory using identical code segment)
    2. Segment = (VA & SEG_MASK) >>SEG_SHIFT
    3. Offset = VA & OFF_Mask
    4. Segmentation cons:
        1. Requires ____ block of memory for each segment
            1. Can lead to _____ and _____

Revision

1. Large contiguous memory causes problems
    1. What happens if we map every byte of VA to a byte of PA?
        1. Reduces fragmentation?
            1. External?
            2. Internal?
        2. How much space needed per-process to store mapping?
2. Middle ground?

Revision : Paging



Example

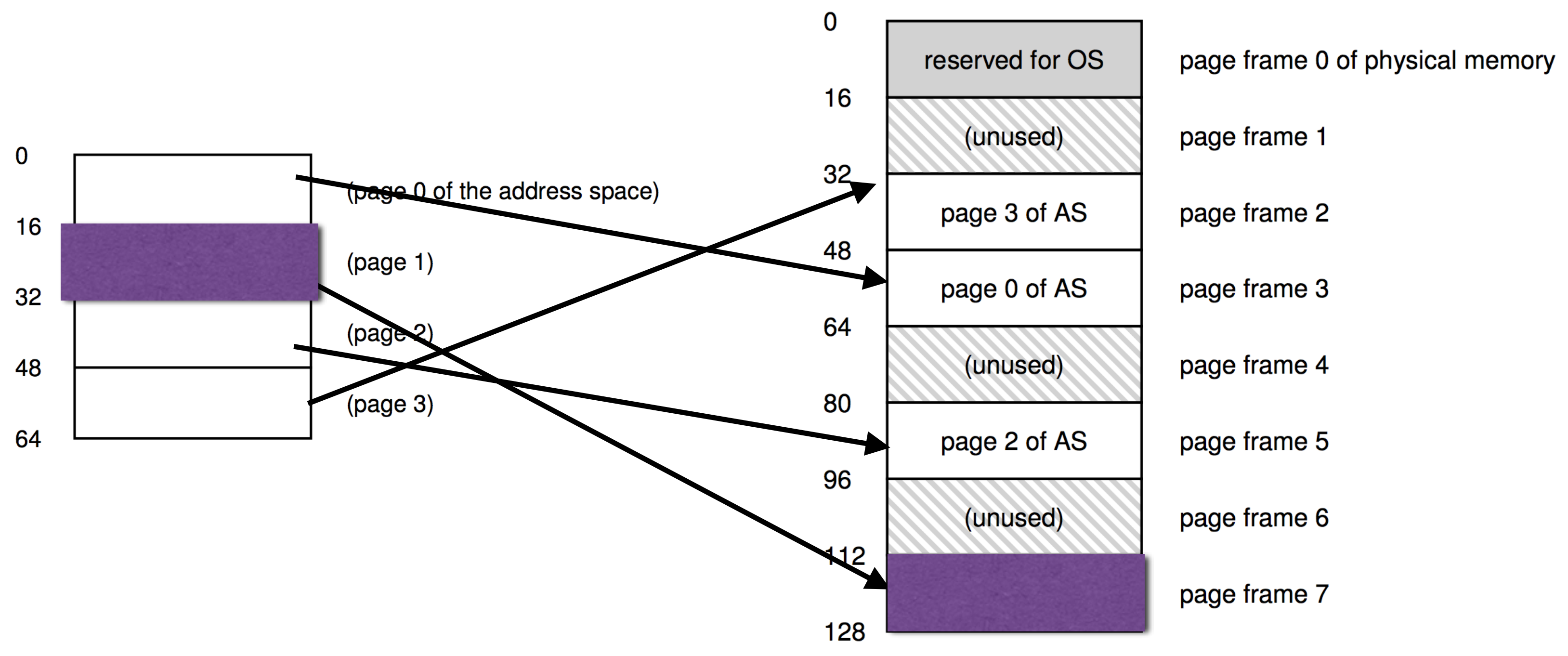
movl 21, %eax

VPN | Offset

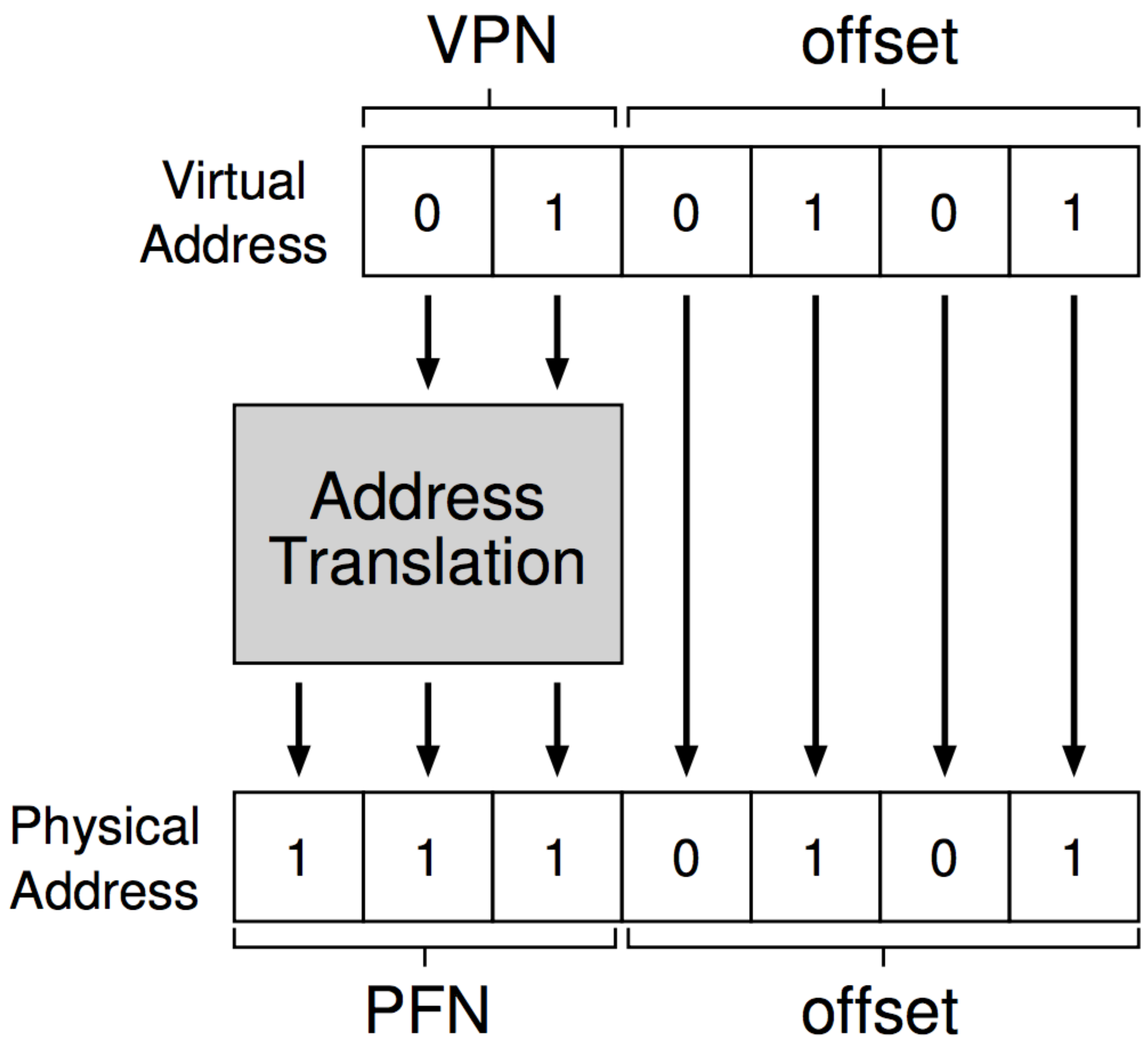
01 | 0101

PFN | Offset

111 | 0101



Address Translation Summary



Page Table Storage

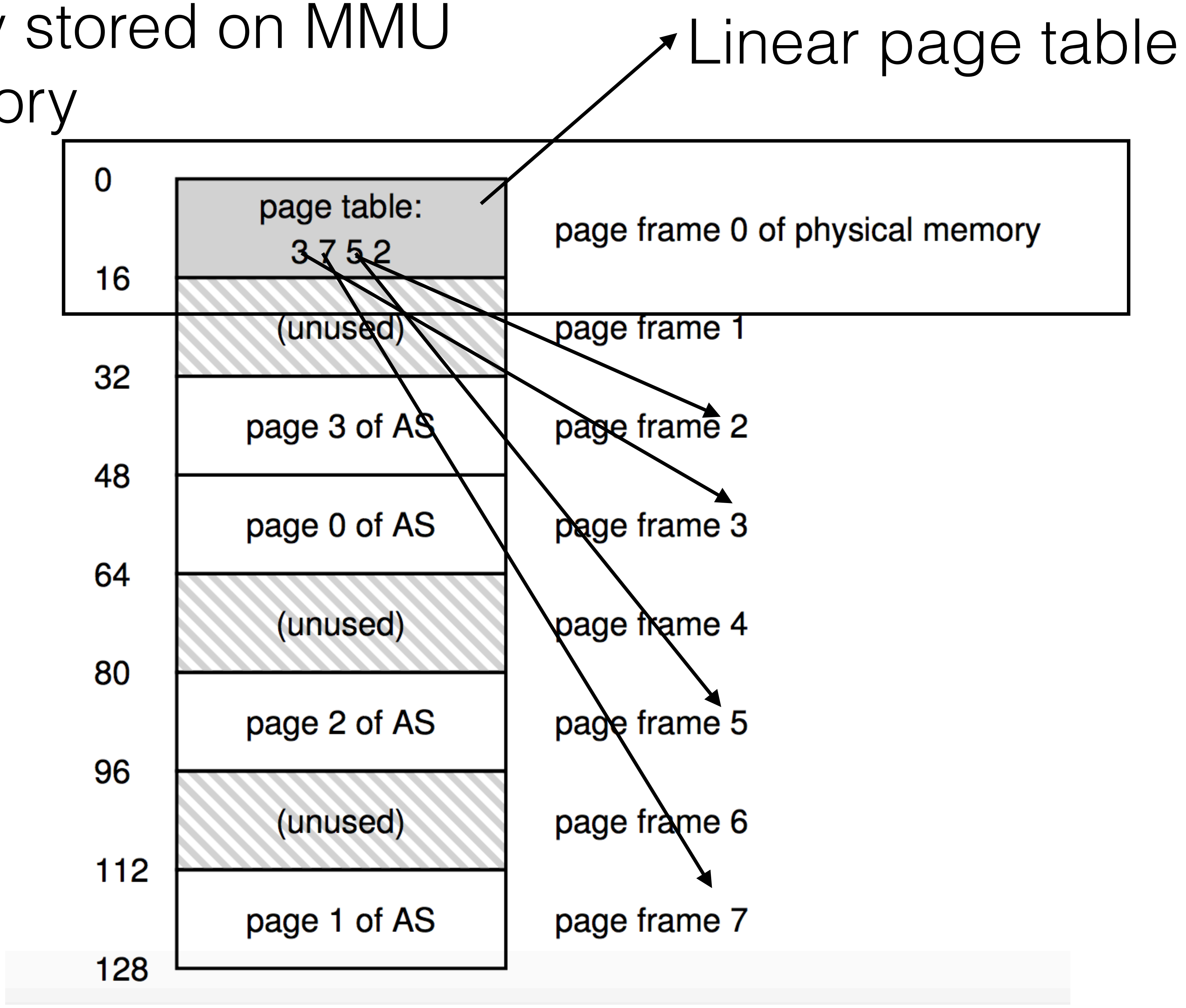
- Let’s consider 32 bit address space
- 32 bit address space with 4 KB pages
- 4 KB pages -> ____ bits?
  - 12 bits Offset
- Remaining bits = 32 - 12 = 20
  - 20 bit VPN
  - # pages = 2^20
  - # translations required = ____
    - 2^20
- 4 bytes per translation -> 4 * 2^20 MB = 4 MB/ process

Page Size Tradeoffs?

- Small size
  - More # of translations
    - More memory overhead/process
    - Less chances of fragmentation
- Large size
  - Less # of translations
    - Less memory overhead/process
    - More chances of fragmentation

Page Table Storage

Not really stored on MMU
- In memory



What else is in the Page Table?

- Protection bit : Read/Write/Execute?
- Present bit: On Memory or HDD/SSD?
- Reference bit: Is the page popular/being referenced?
    - Else?
- Valid bit: Is translation valid?
- Dirty bit: Modified since brought to memory?

Worked Out Example

```
int array[1000];
...
for (i = 0; i < 1000; i++)
    array[i] = 0;
```

```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

$$\xleftarrow{} *(EDI + 4*EAX) = 0$$

Worked Out Example

```
int array[1000];
...
for (i = 0; i < 1000; i++)
    array[i] = 0;
```

```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Address of array[0]

*(EDI + 4*EAX) = 0

Worked Out Example

```
int array[1000];
...
for (i = 0; i < 1000; i++)
    array[i] = 0;
```

Index into array (i)

```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

*(EDI + 4*EAX) = 0

Worked Out Example

```
int array[1000];
...
for (i = 0; i < 1000; i++)
    array[i] = 0;
```

Index into array (i)

```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

*(EDI + 4*EAX) = 0

I = I + 1

Worked Out Example

```
int array[1000];
...
for (i = 0; i < 1000; i++)
    array[i] = 0;
```

Index into array (i)

```
1024 movl  $0x0,(%edi,%eax,4)
1028 incl  %eax
1032 cmpl  $0x03e8,%eax
1036 jne   0x1024
```

*(EDI + 4*EAX) = 0

I = I + 1

Is I == 1000

Worked Out Example

```
int array[1000];
...
for (i = 0; i < 1000; i++)
    array[i] = 0;
```

Index into array (i)

```
1024 movl  $0x0,(%edi,%eax,4)
1028 incl  %eax
1032 cmpl  $0x03e8,%eax
1036 jne   0x1024
```

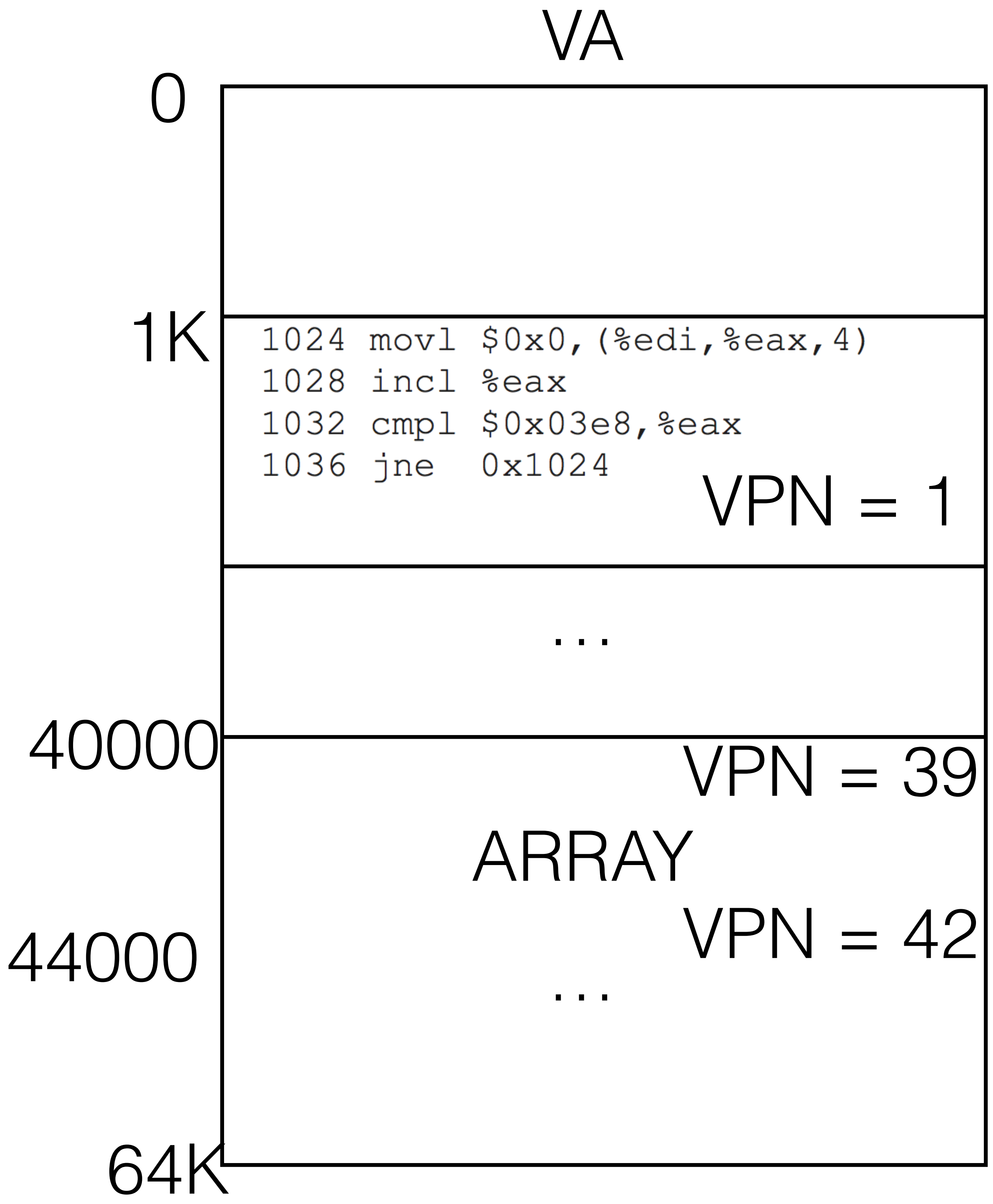
*(EDI + 4*EAX) = 0

I = I + 1

Is I == 1000

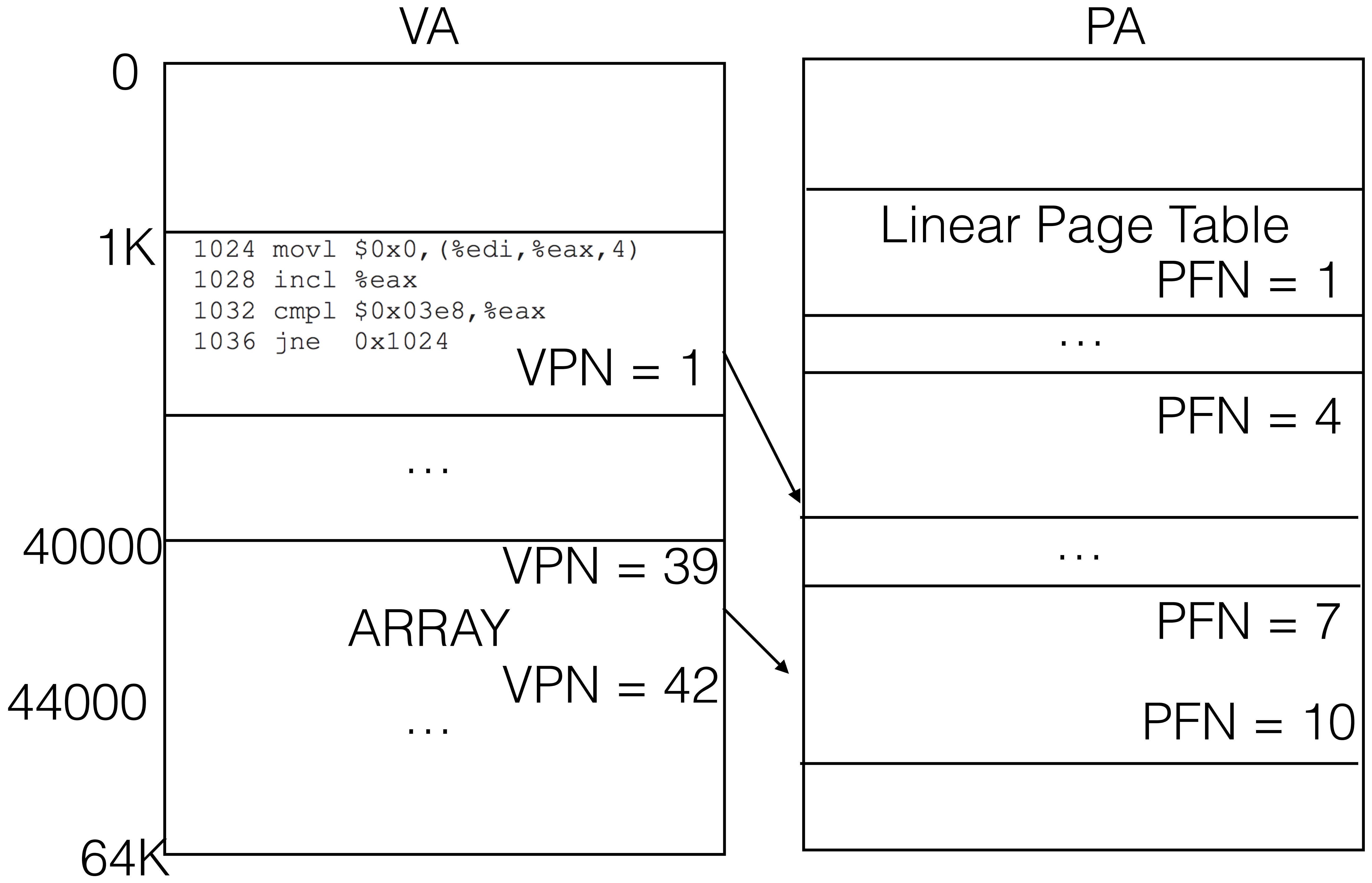
If Above is False

Worked Out Example



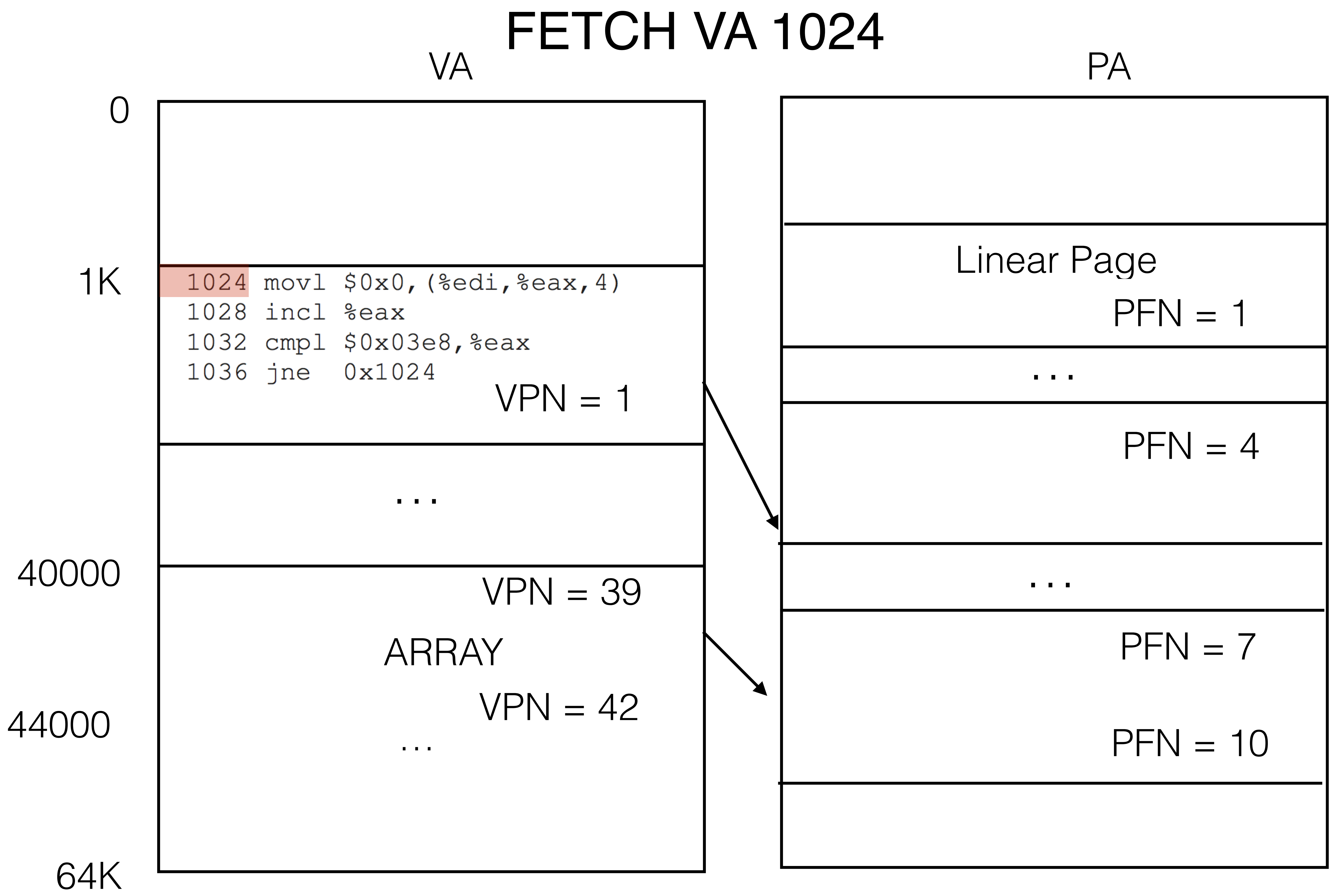
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example



```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

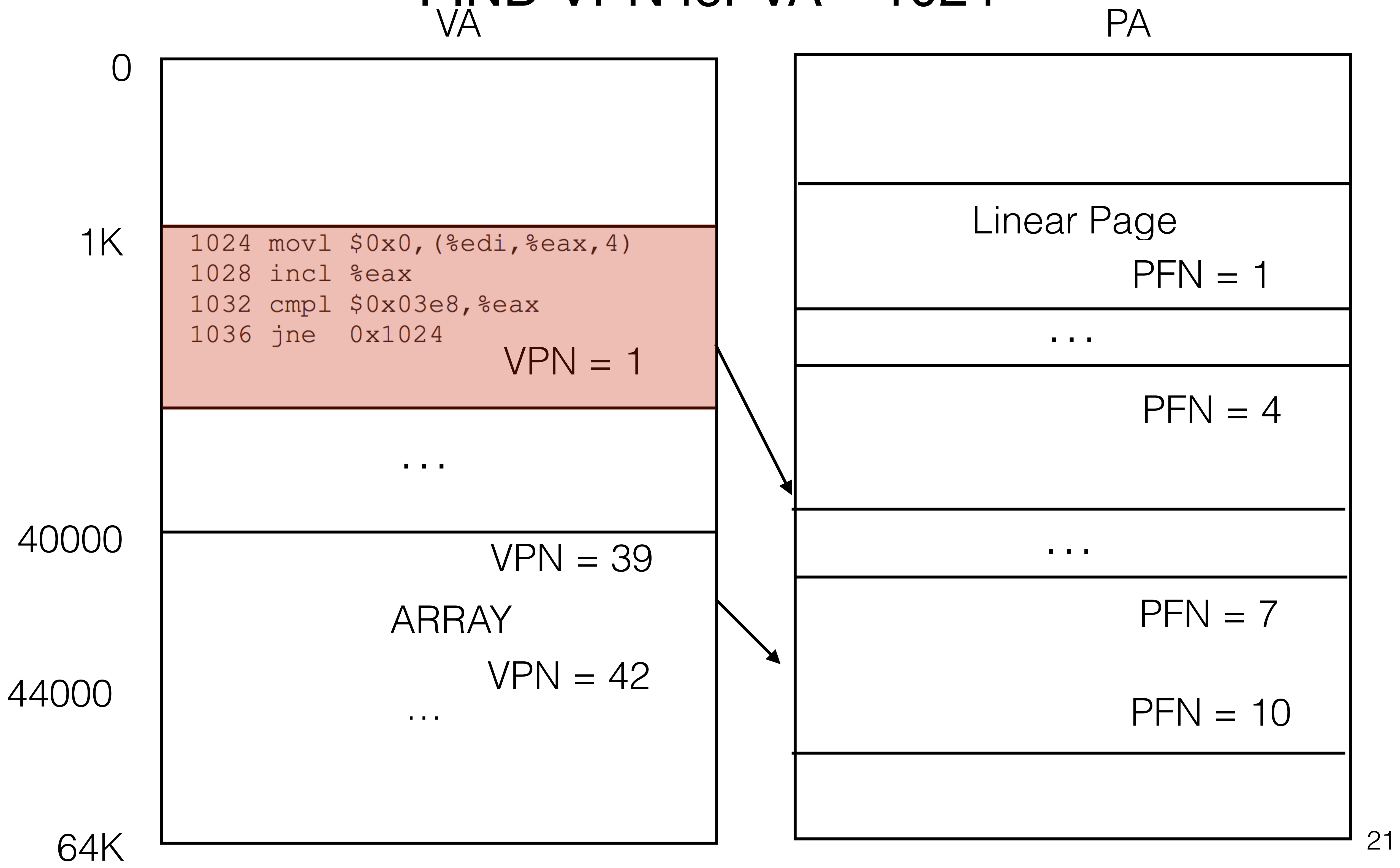
Worked Out Example



```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

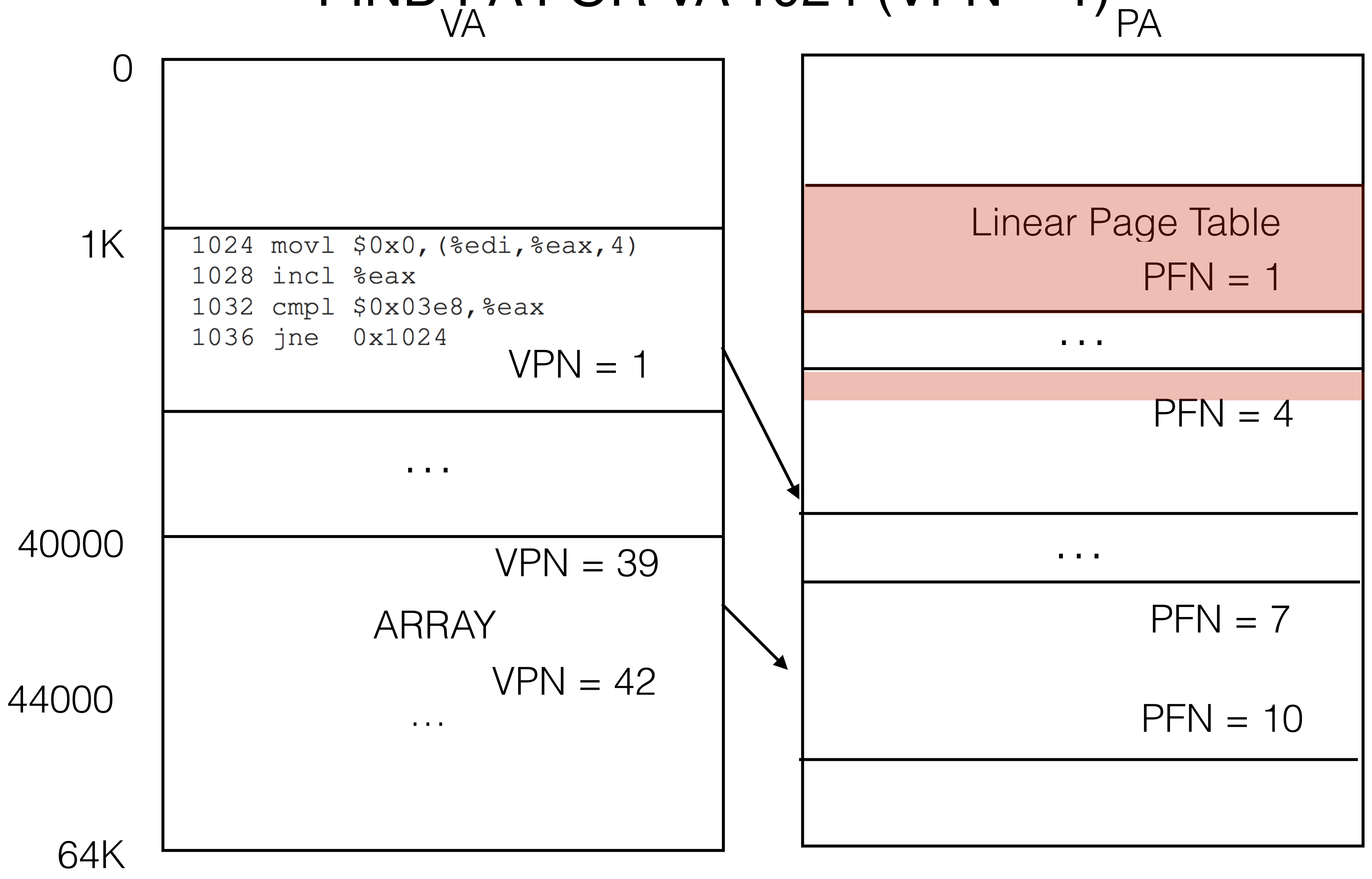
FIND VPN for VA = 1024



```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

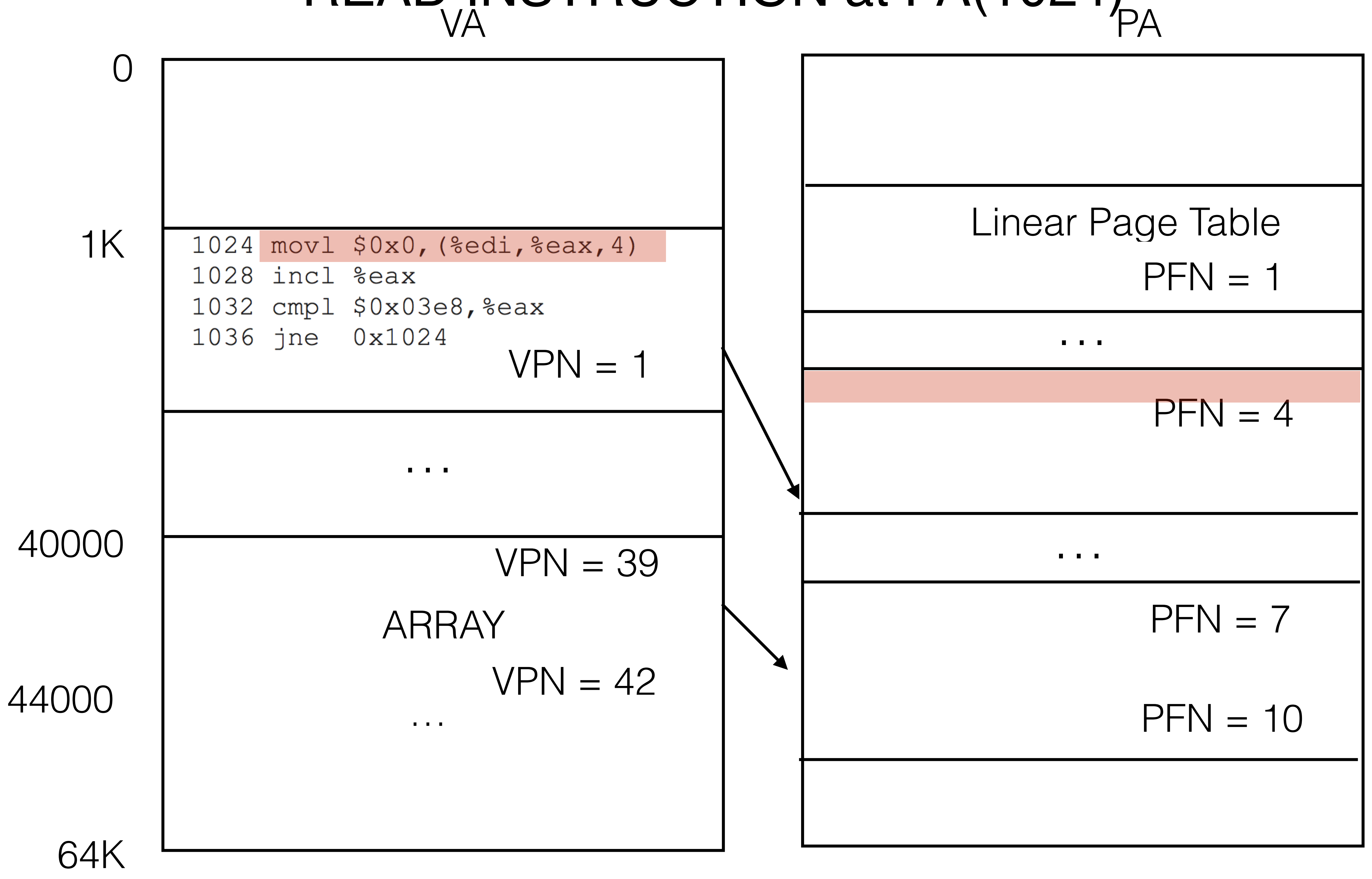
FIND PA FOR VA 1024 (VPN = 1)



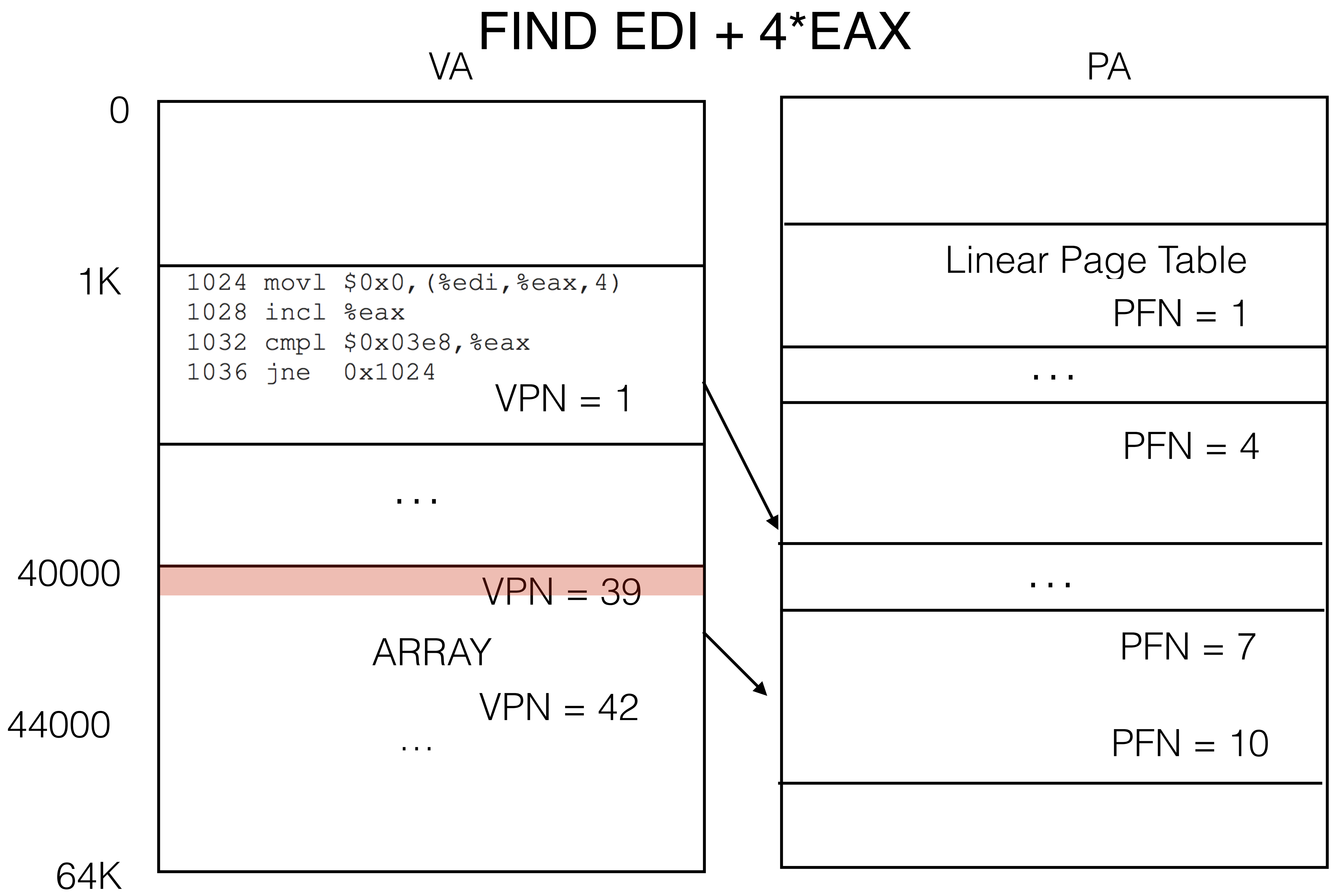
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

READ INSTRUCTION at PA(1024)



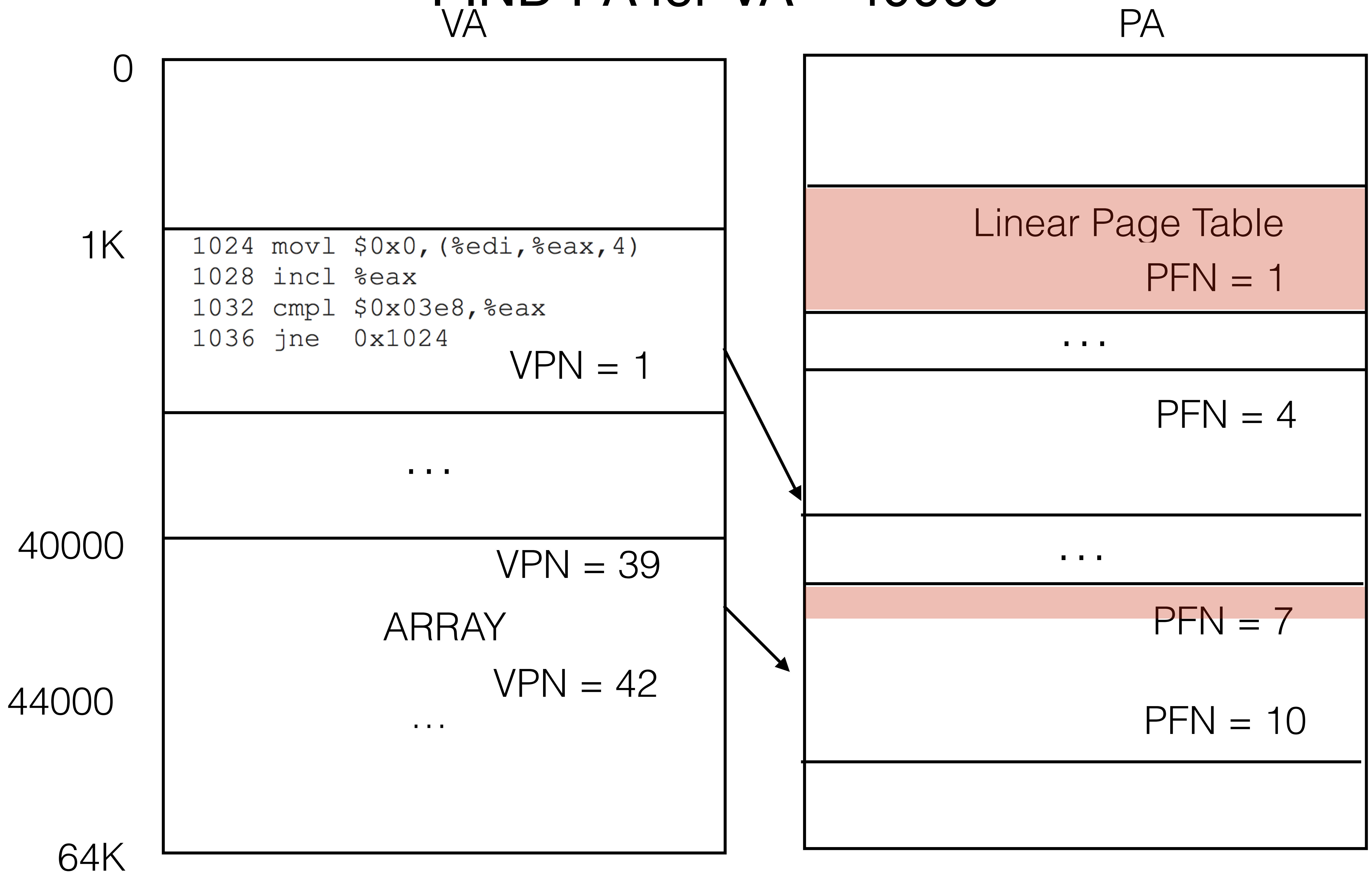
Worked Out Example



```
1024 movl  $0x0,(%edi,%eax,4)
1028 incl  %eax
1032 cmpl  $0x03e8,%eax
1036 jne   0x1024
```

Worked Out Example

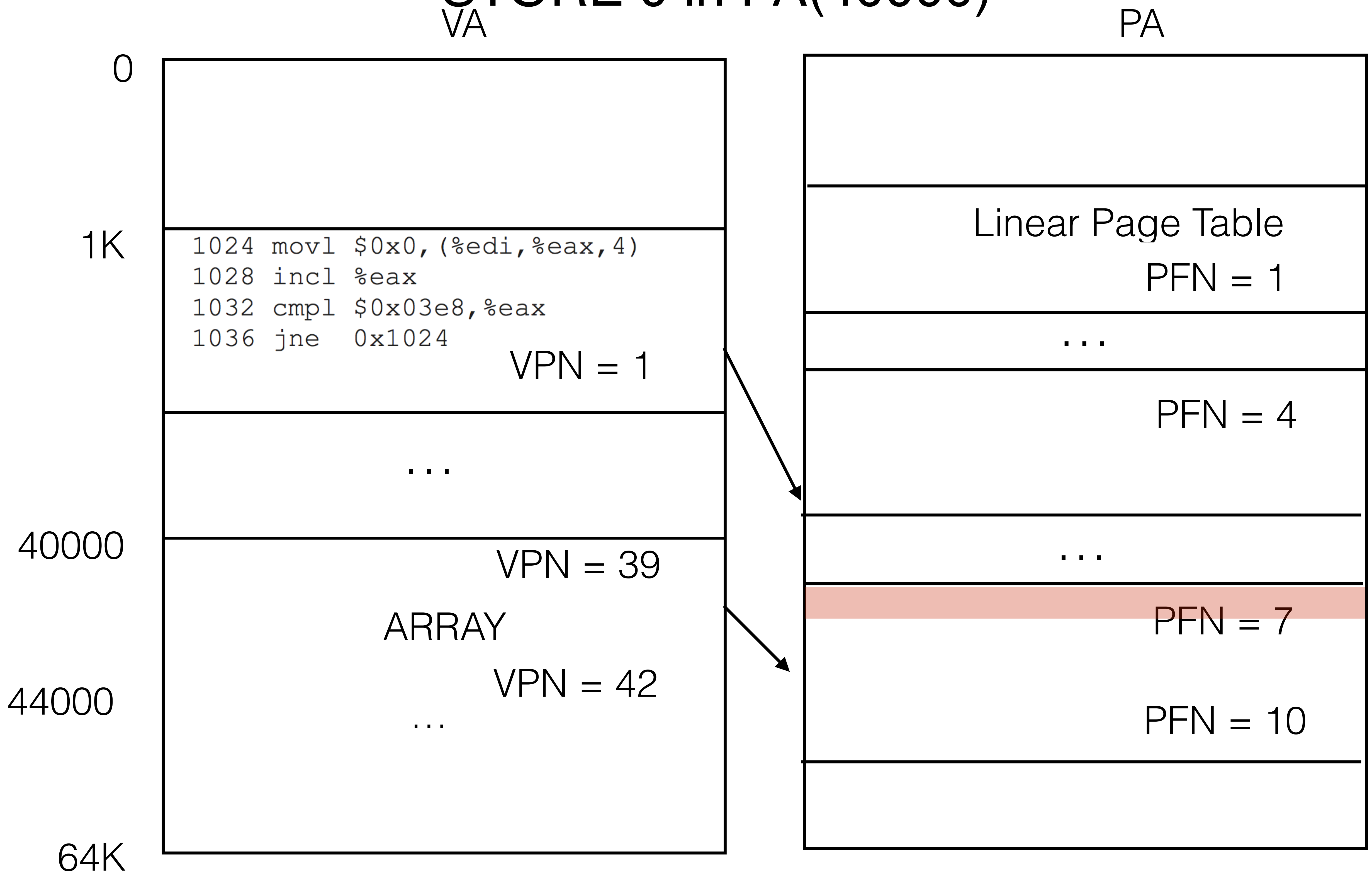
FIND PA for VA = 40000



```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

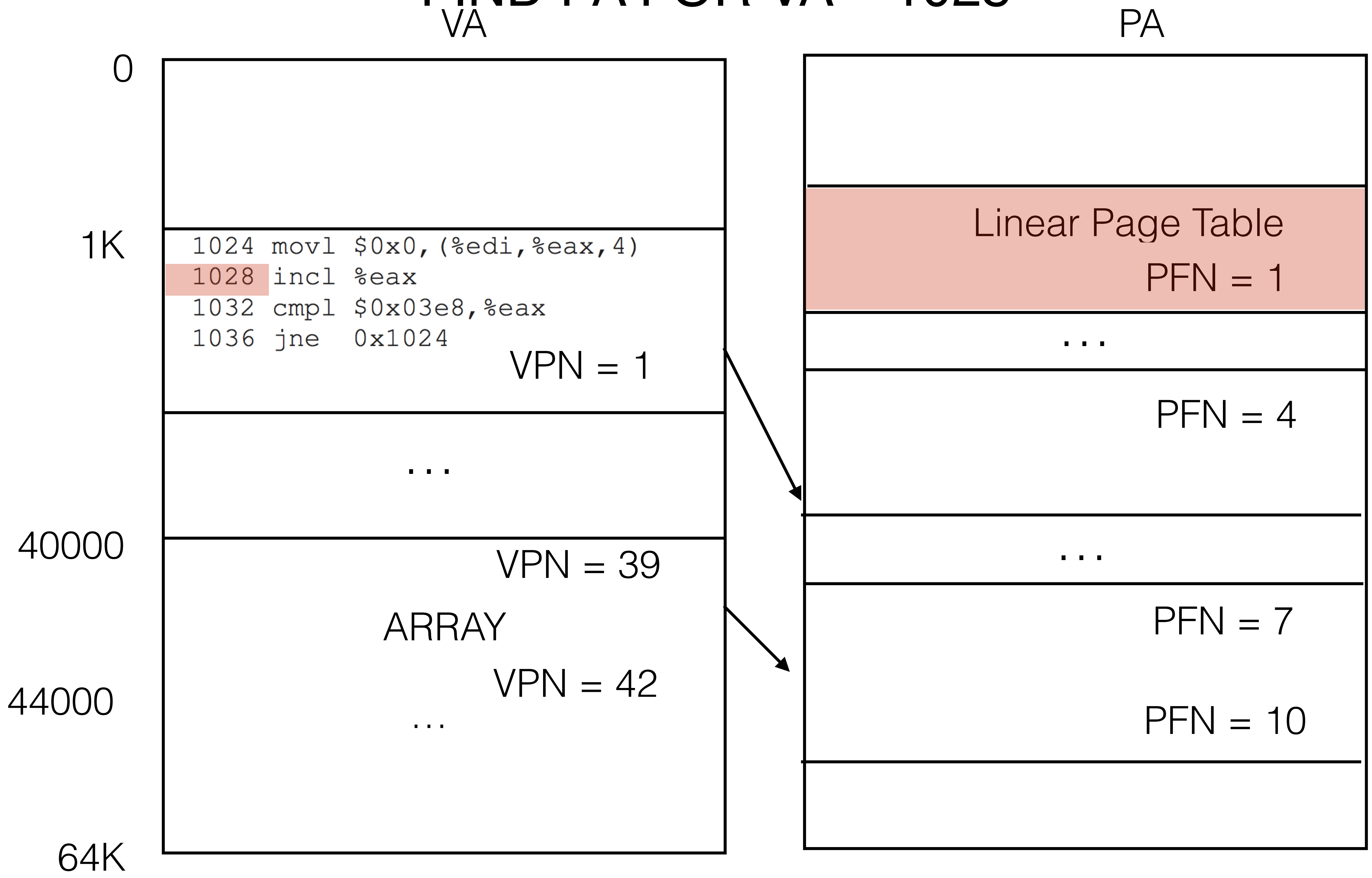
STORE 0 in PA(40000)



```
1024 movl  $0x0,(%edi,%eax,4)
1028 incl  %eax
1032 cmpl  $0x03e8,%eax
1036 jne   0x1024
```

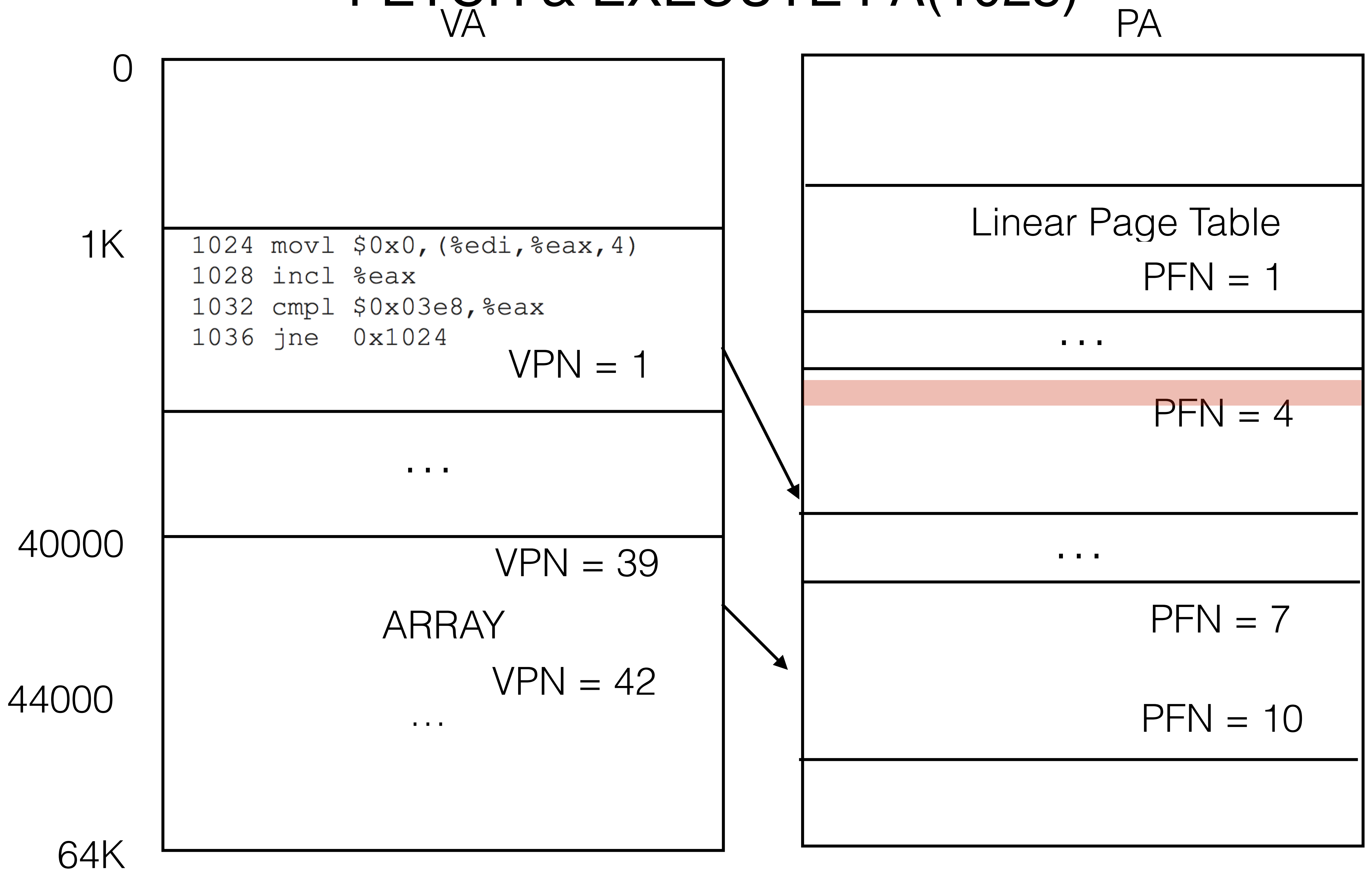
Worked Out Example

FIND PA FOR VA = 1028



Worked Out Example

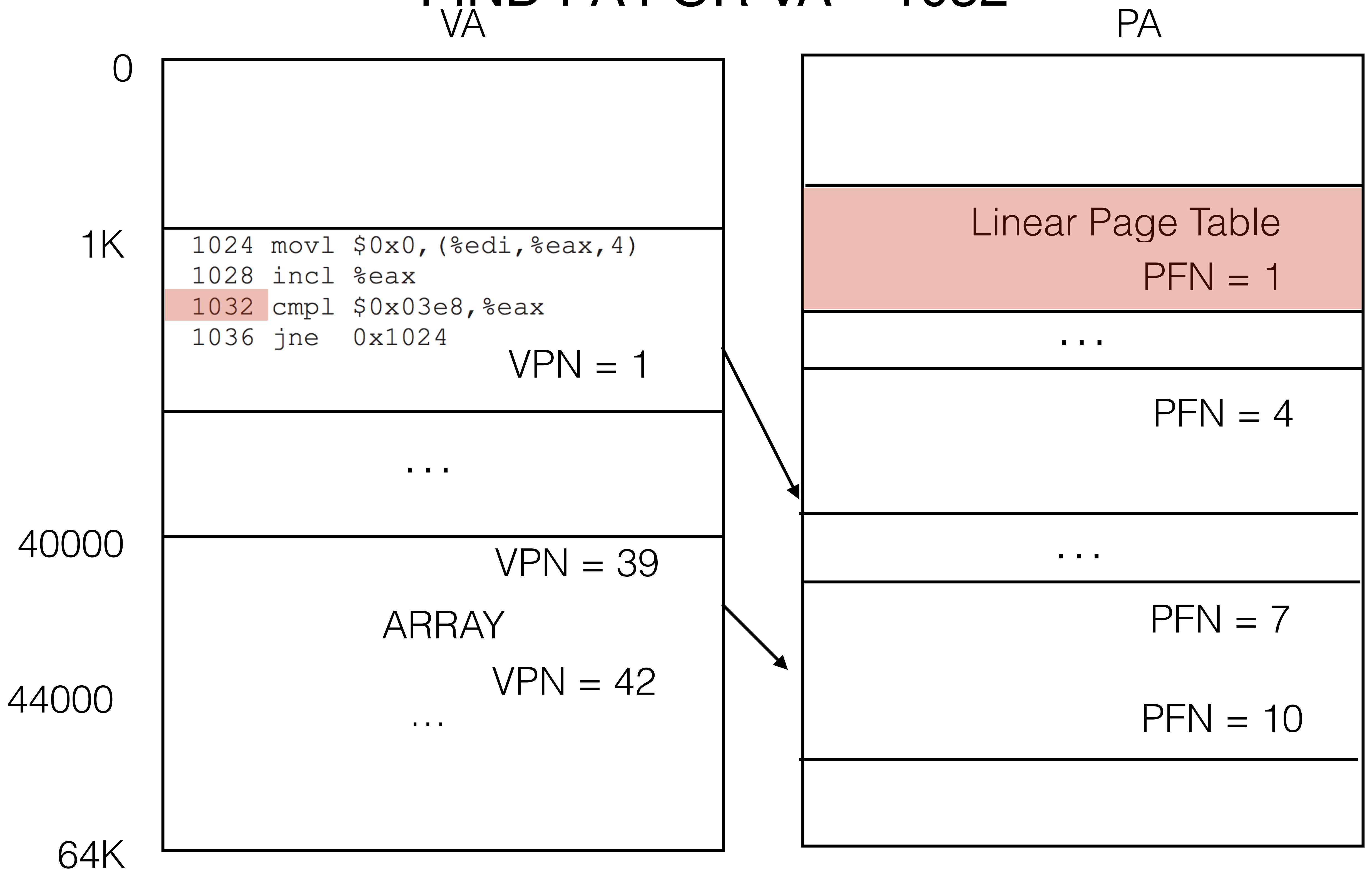
FETCH & EXECUTE PA(1028)



```
1024 movl  $0x0,(%edi,%eax,4)
1028 incl  %eax
1032 cmpl  $0x03e8,%eax
1036 jne   0x1024
```

Worked Out Example

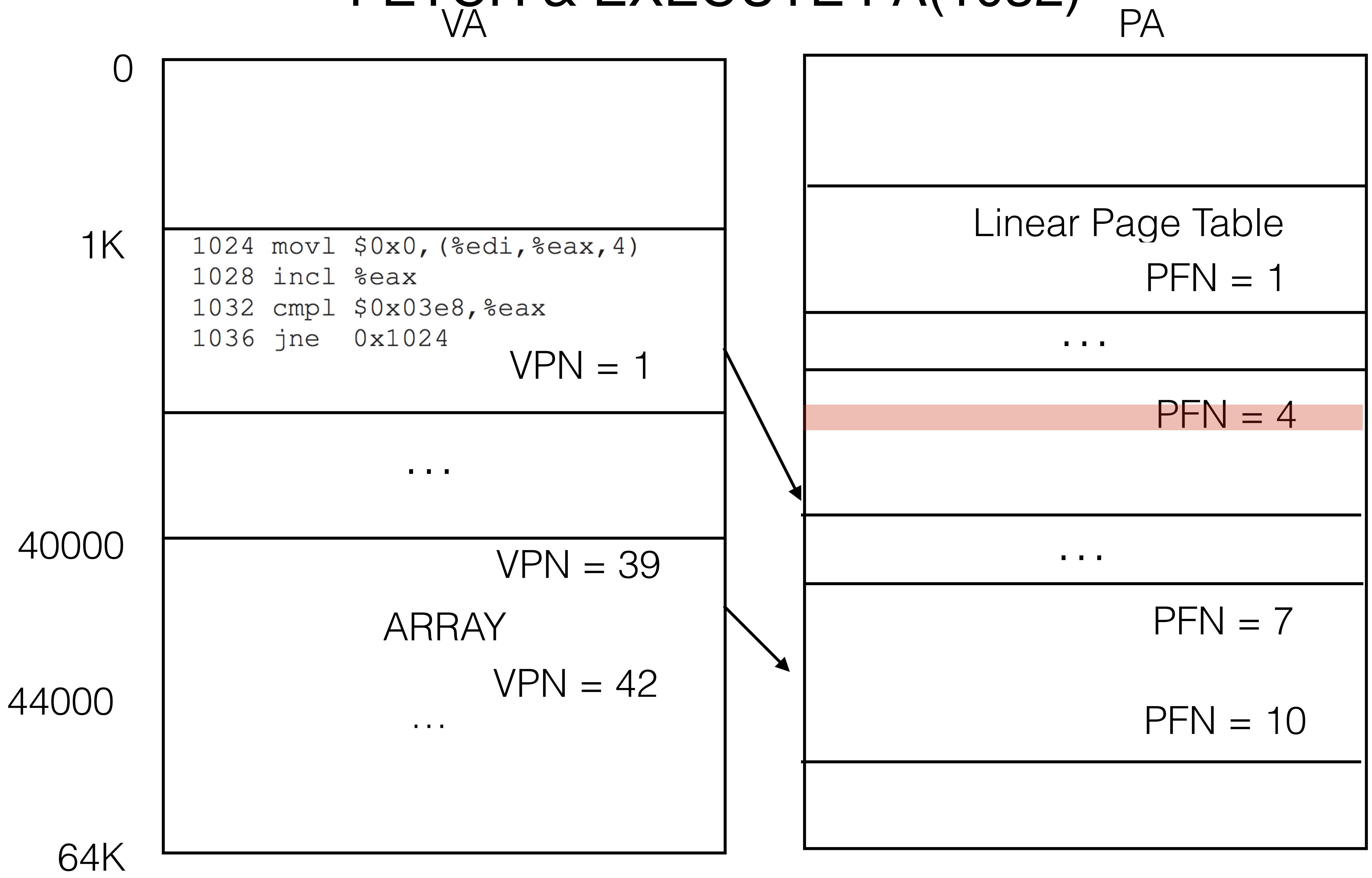
FIND PA FOR VA = 1032



```
1024 movl  $0x0,(%edi,%eax,4)
1028 incl  %eax
1032 cmpl  $0x03e8,%eax
1036 jne   0x1024
```

Worked Out Example

FETCH & EXECUTE PA(1032)



```
1024 movl  $0x0,(%edi,%eax,4)
1028 incl  %eax
1032 cmpl  $0x03e8,%eax
1036 jne   0x1024
```

Example Summary

1. Extract VPN (virt page num) from VA (virt addr)
2. Calculate addr of PTE (page table entry)
3. Read PTE from memory
4. Extract PFN (page frame num)
5. Build PA (phys addr)
6. Read contents of PA from memory into register

SLOW!

Caching Makes Sense!

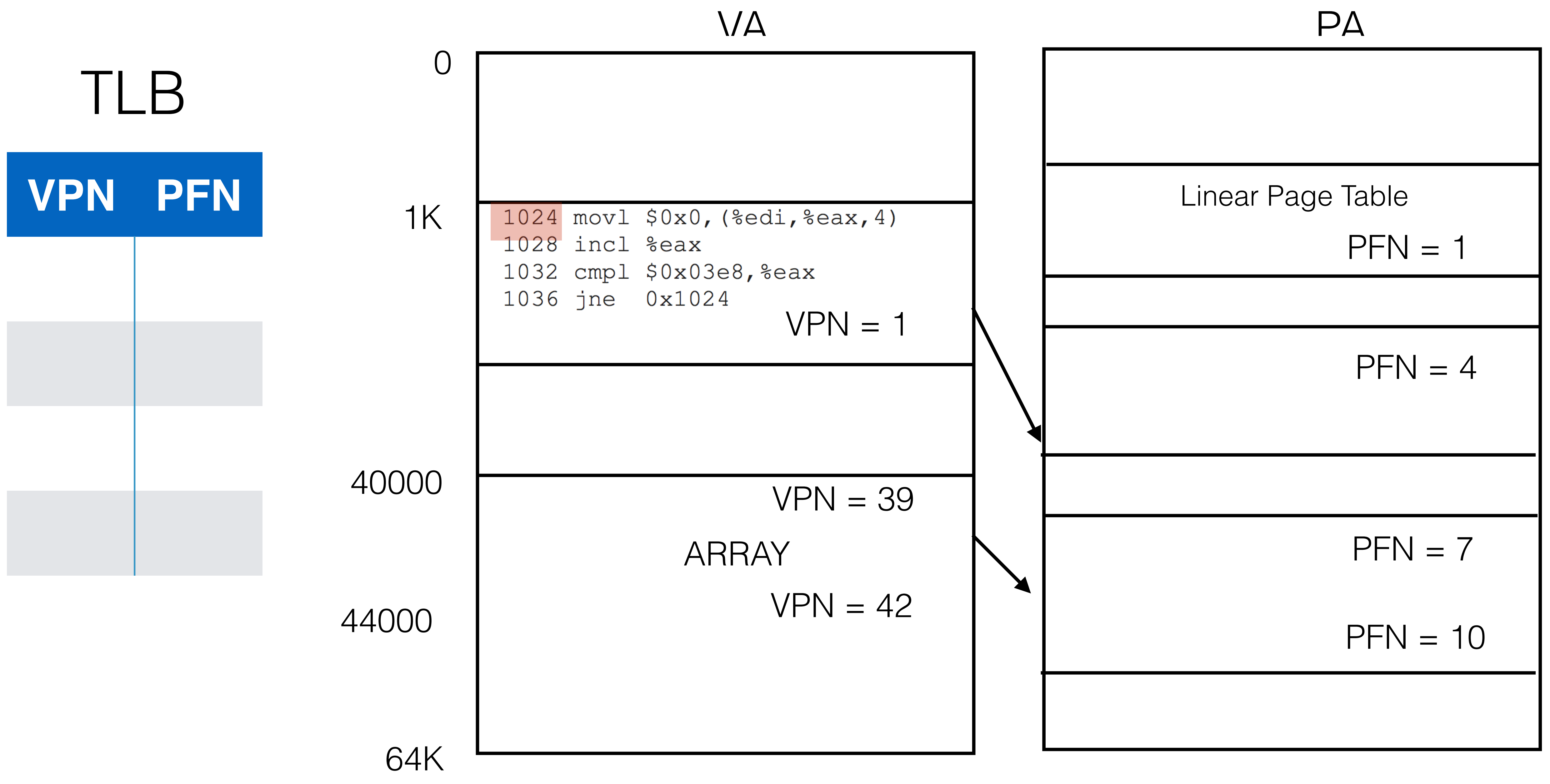
Factorial with and without memoization

Caching - Translation Lookaside Buffer (TLB)

1. Get the VPN from VA
2. Check if TLB has VA
3. If found, it is a TLB Hit. Yay!
    - Extract the PFN from TLB (PFN = TLB[VPN])
    - Generate PA from PFN (Add offset)
    - Access memory assuming protection checks work
4. If not found, it is a TLB Miss. :(
    - Access Page table to find the translation
    - Add translation to TLB (TLB[VPN] = PFN)
    - Goto Step 2

Worked Out Example

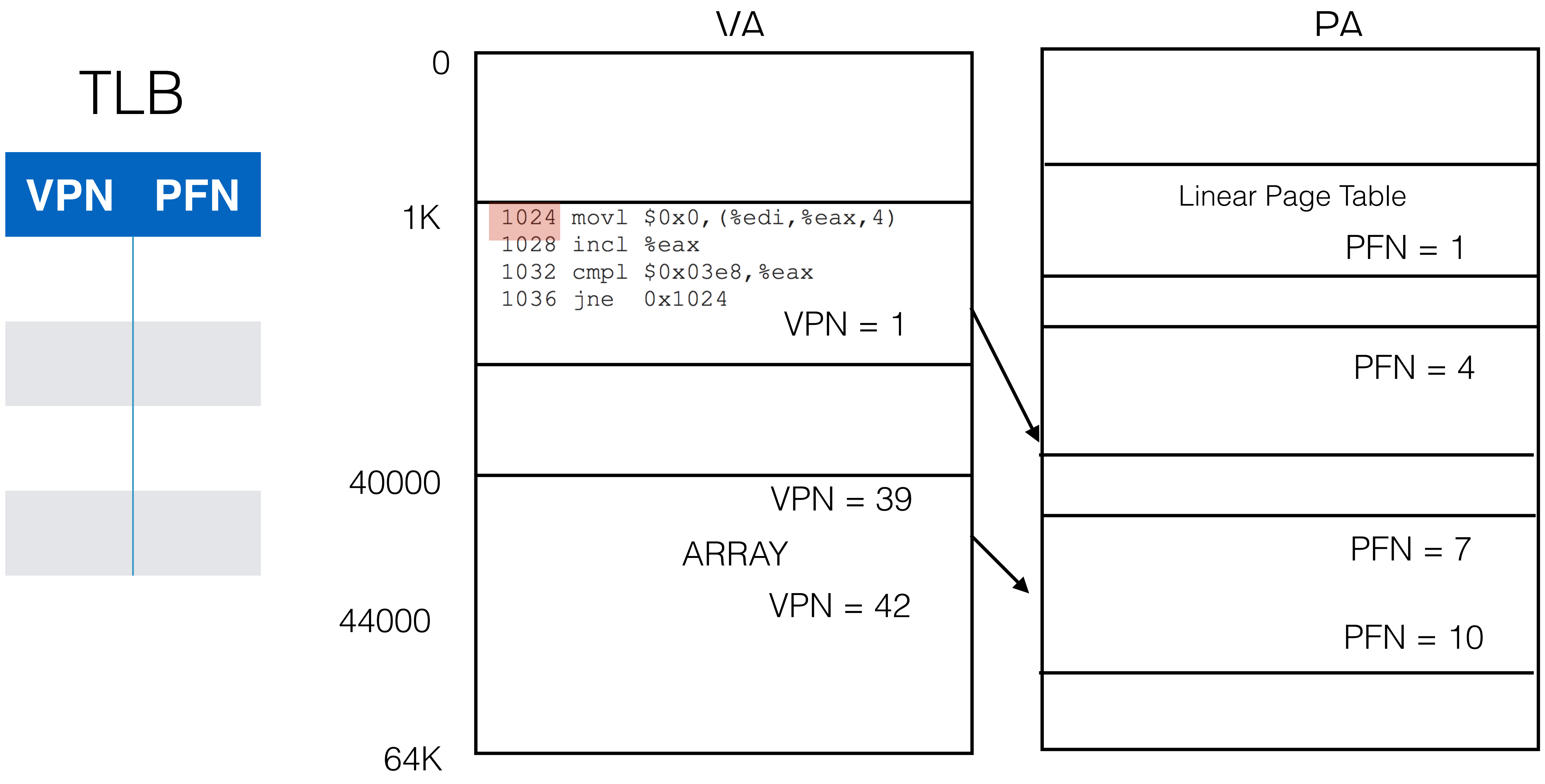
FETCH VA 1024



```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

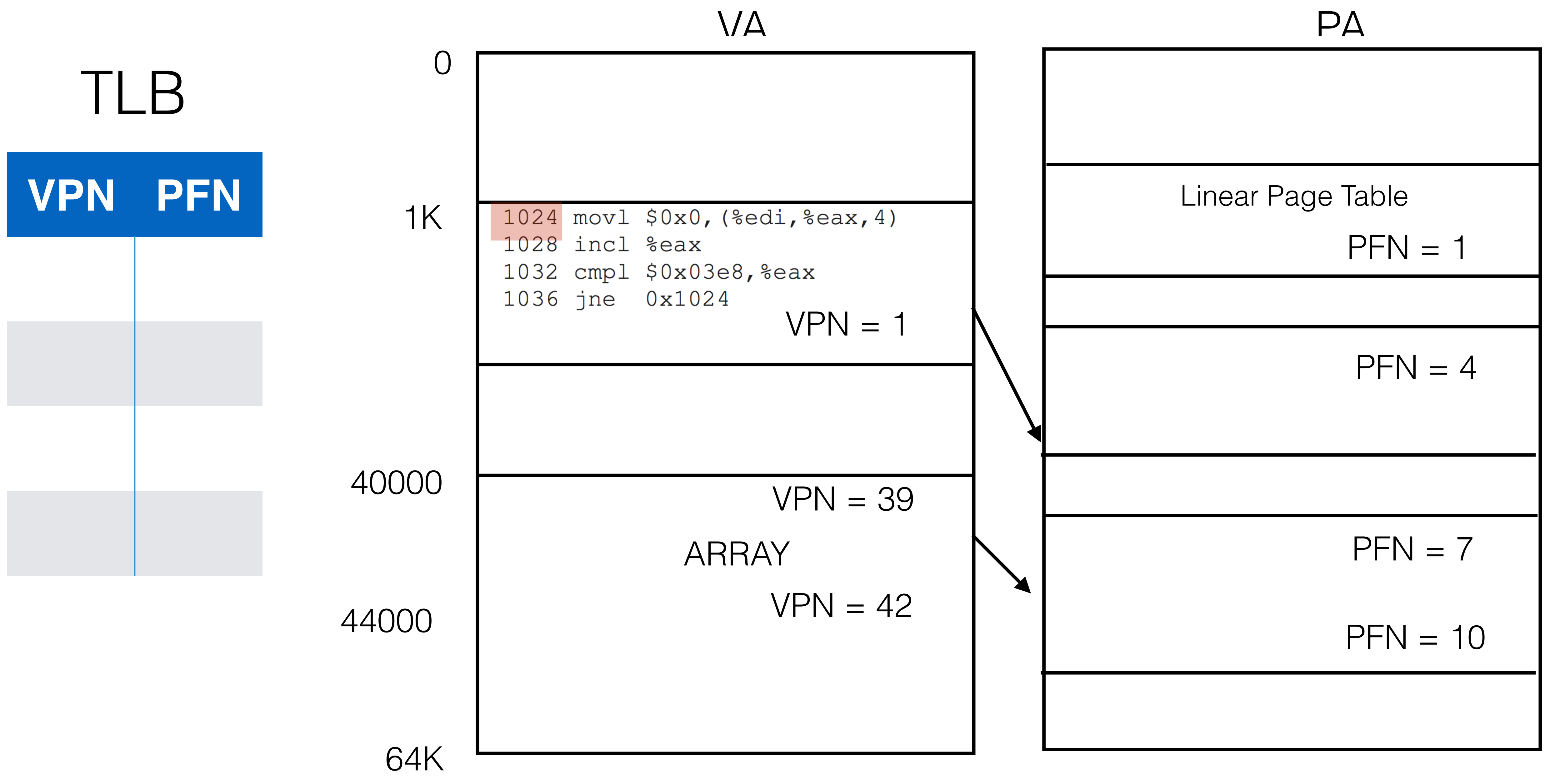
Get VPN for VA 1024. VPN = 1



```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

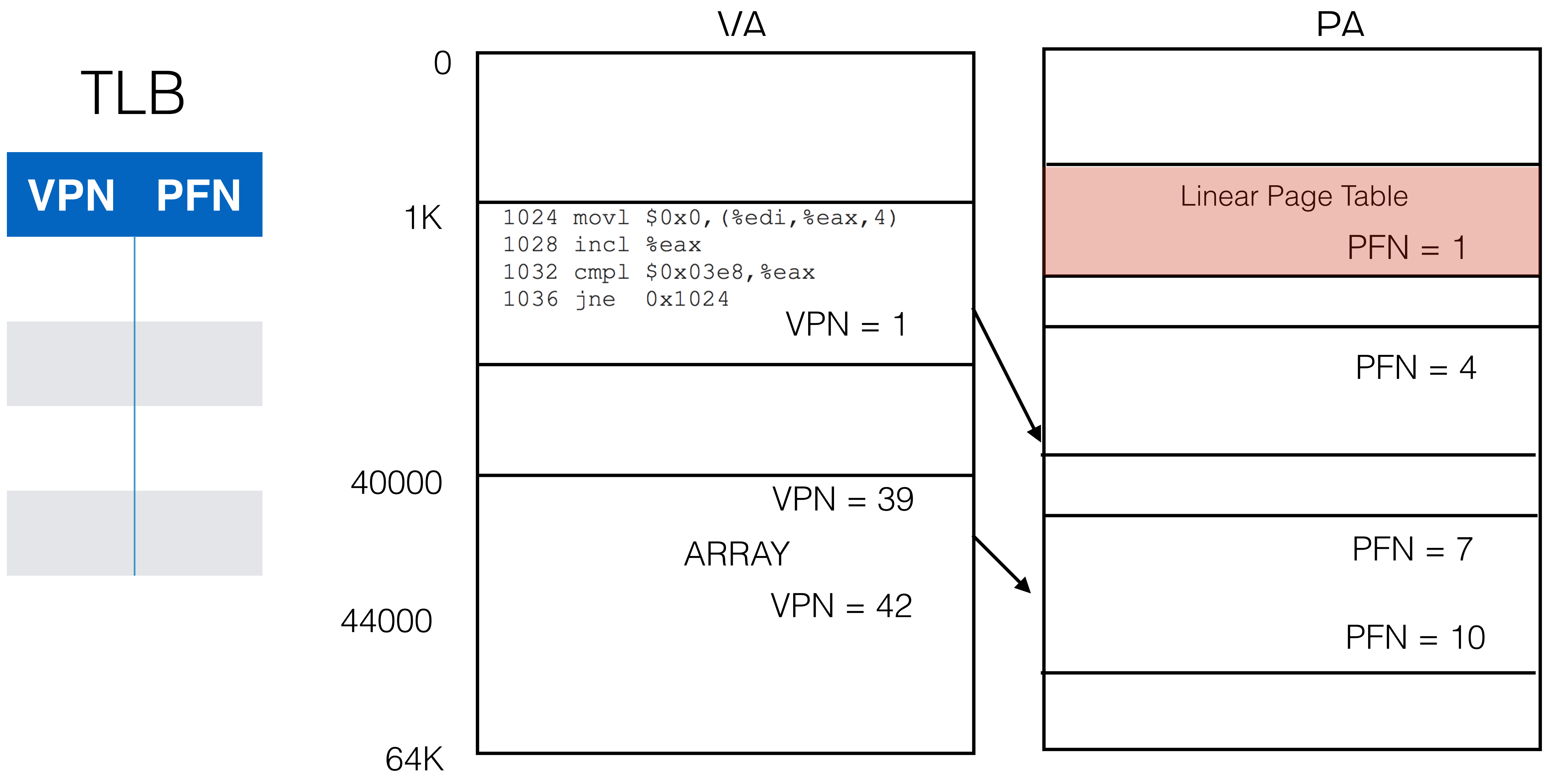
Worked Out Example

LOOK IN TLB for VPN = 1. Not found. TLB Miss!



Worked Out Example

Find PFN for VPN = 1 by accessing Page Table



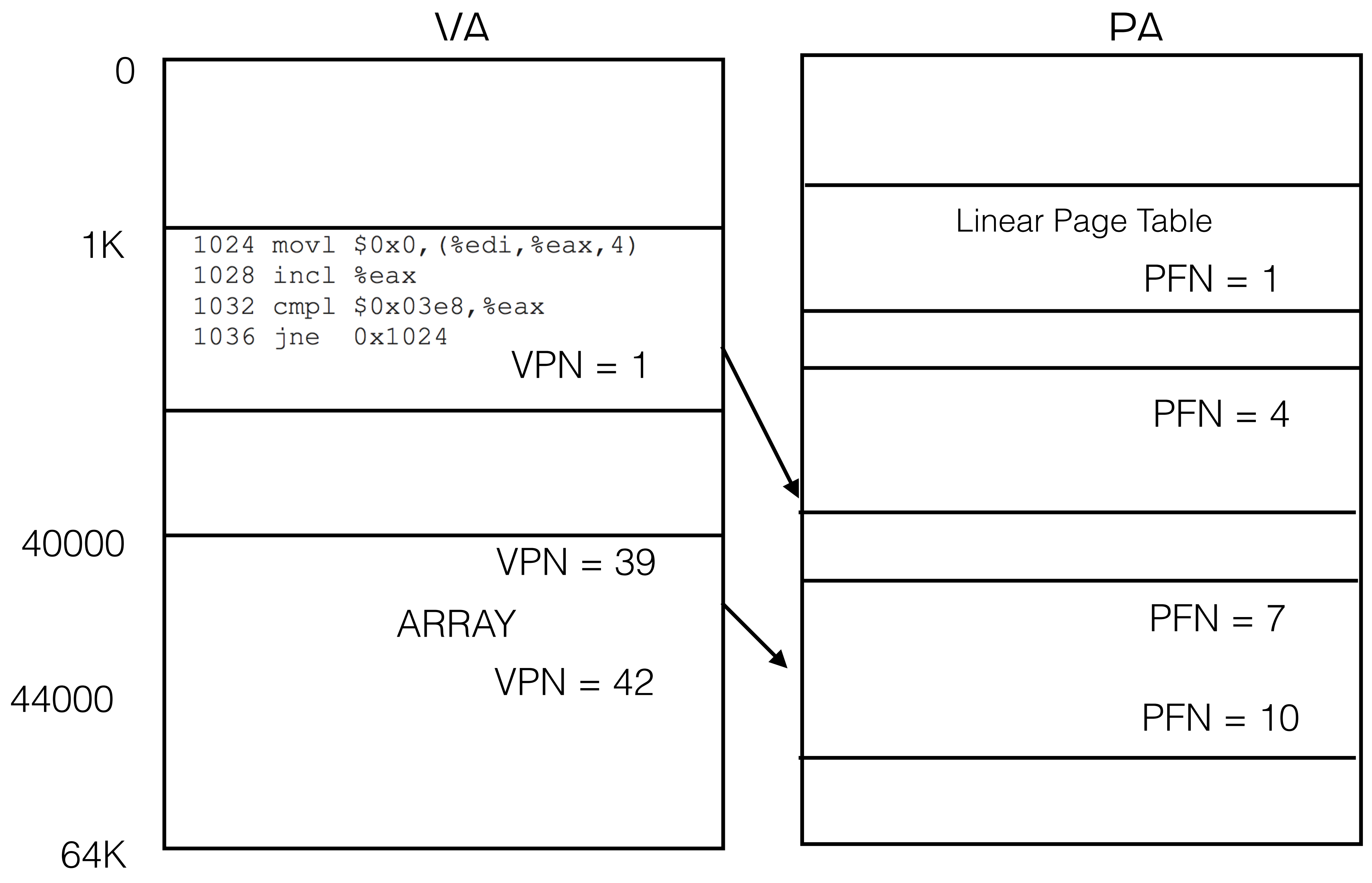
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

Add entry to TLB

TLB

VPN	PFN
1	4



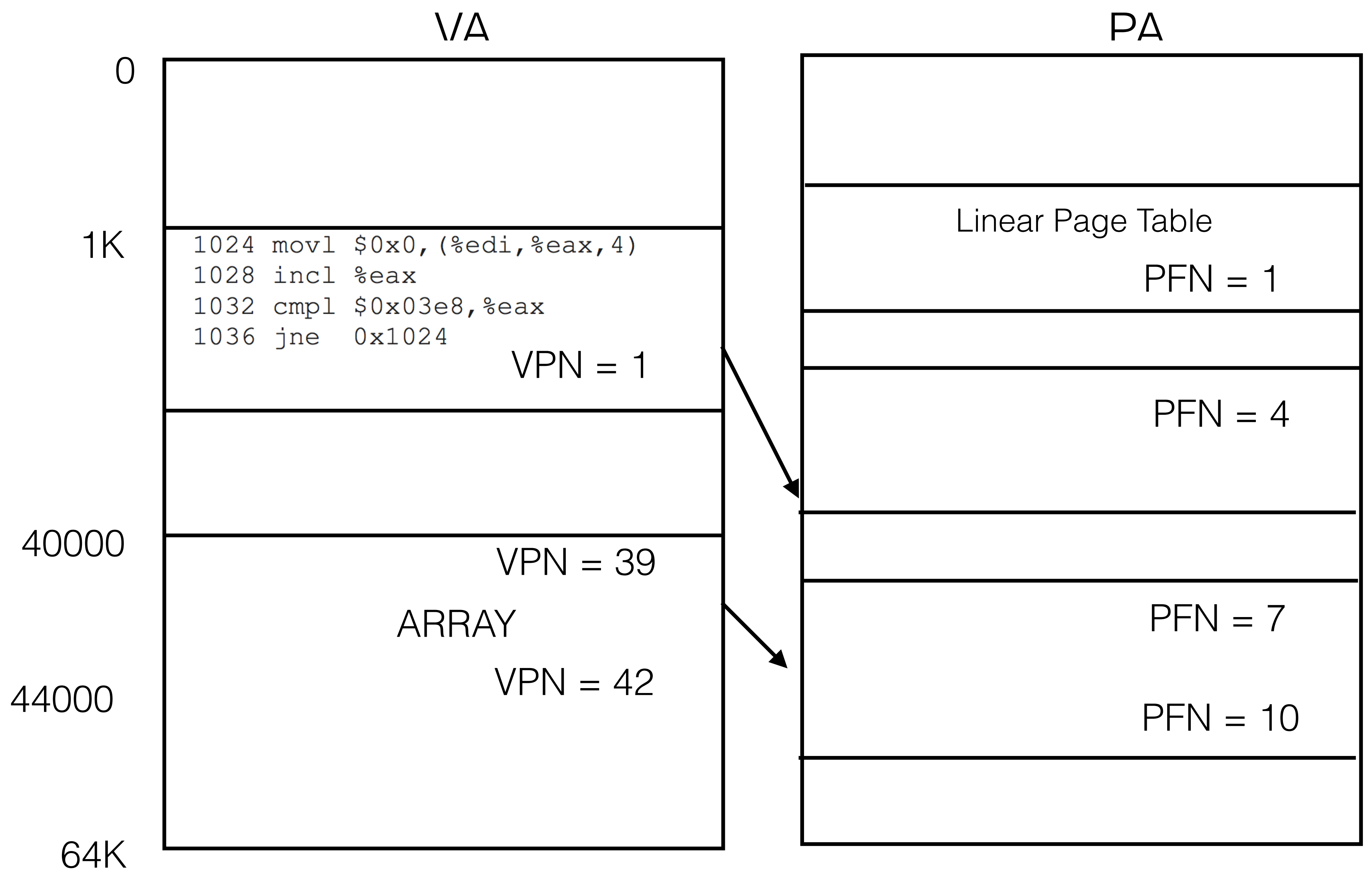
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

Search for translation of VPN = 1 on TLB

TLB

VPN	PFN
1	4



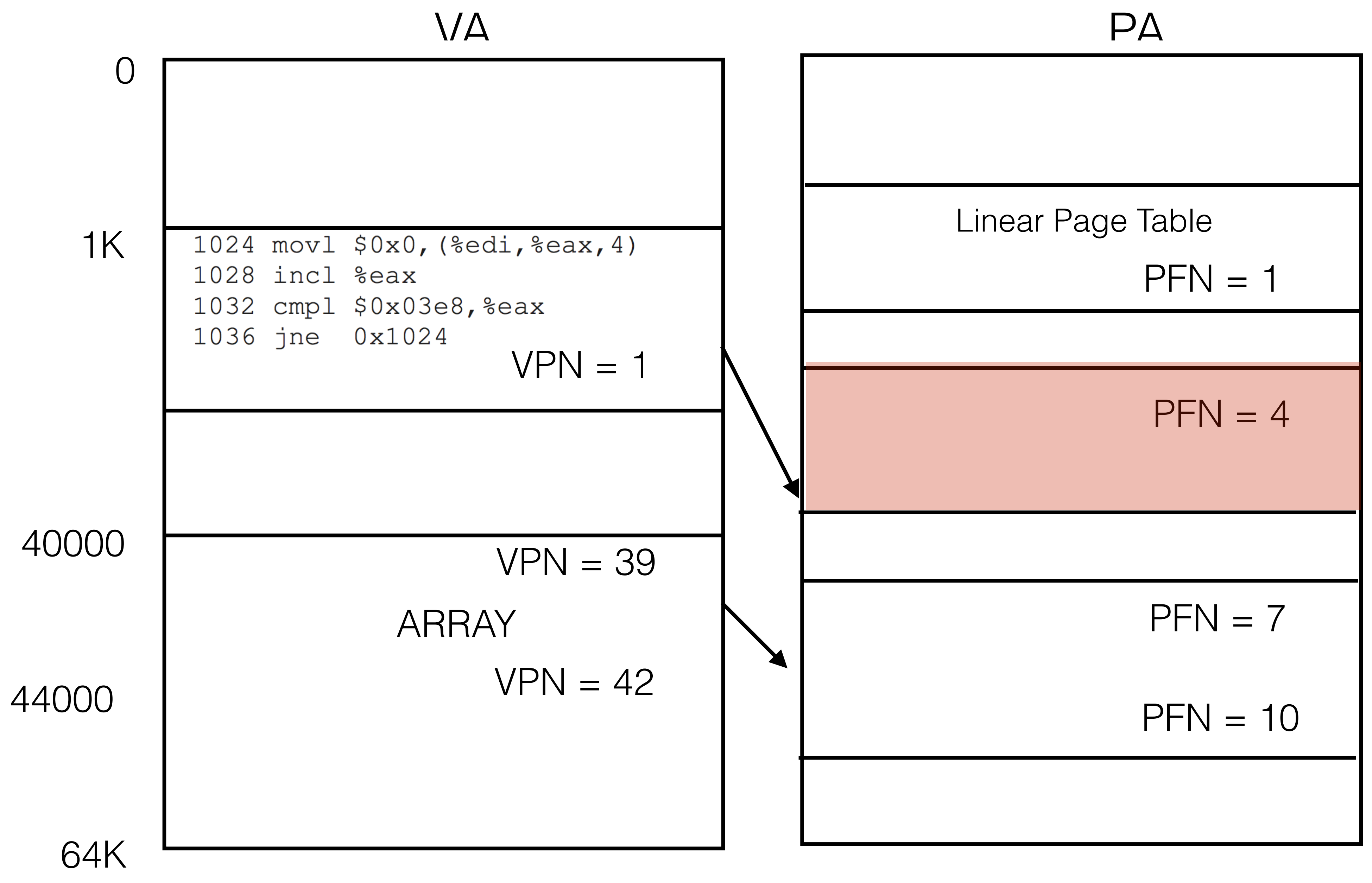
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

Goto PFN 4 and create PA by adding offset

TLB

VPN	PFN
1	4



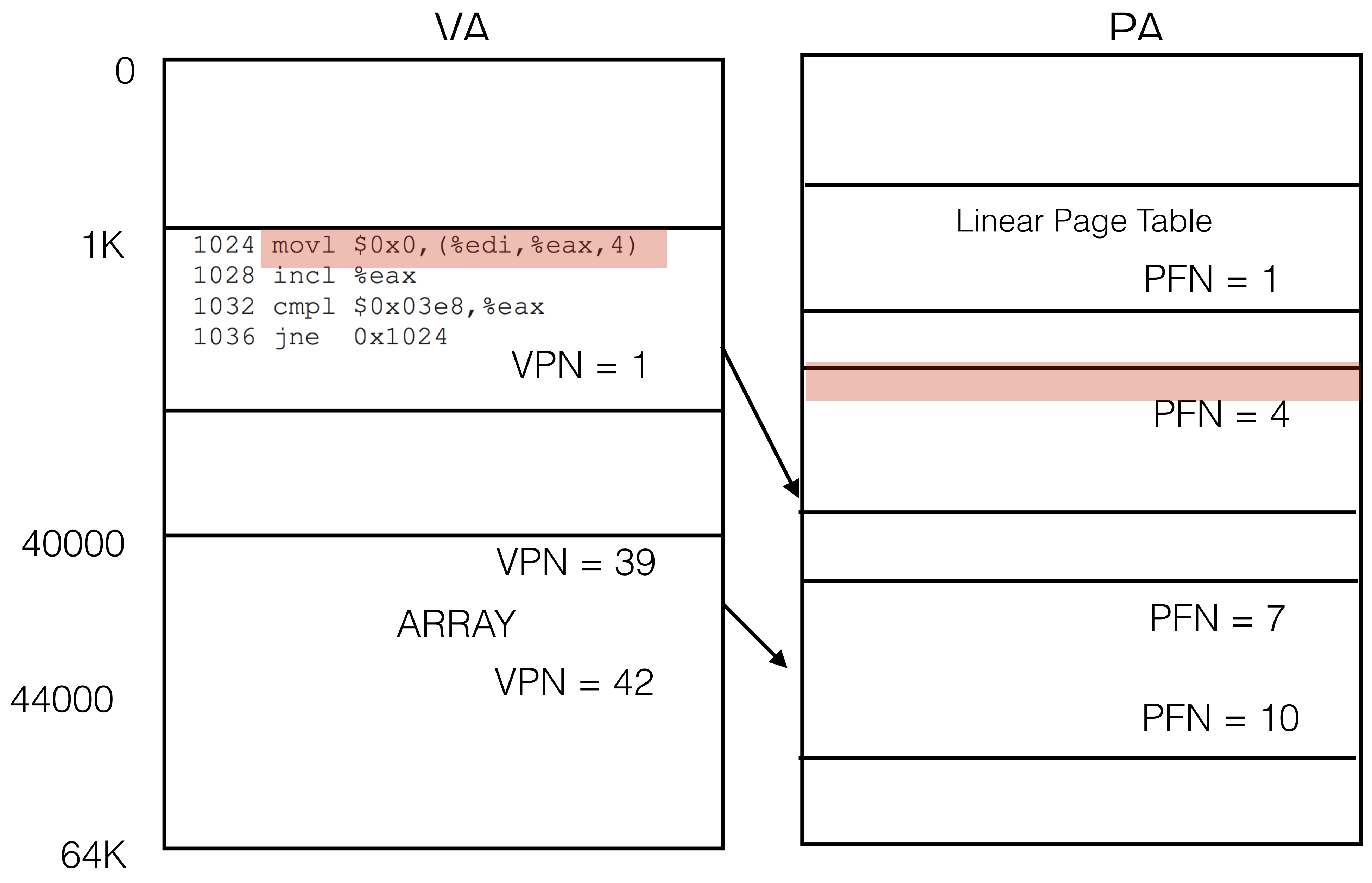
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

READ INSTRUCTION at PA(1024)

TLB

VPN	PFN
1	4



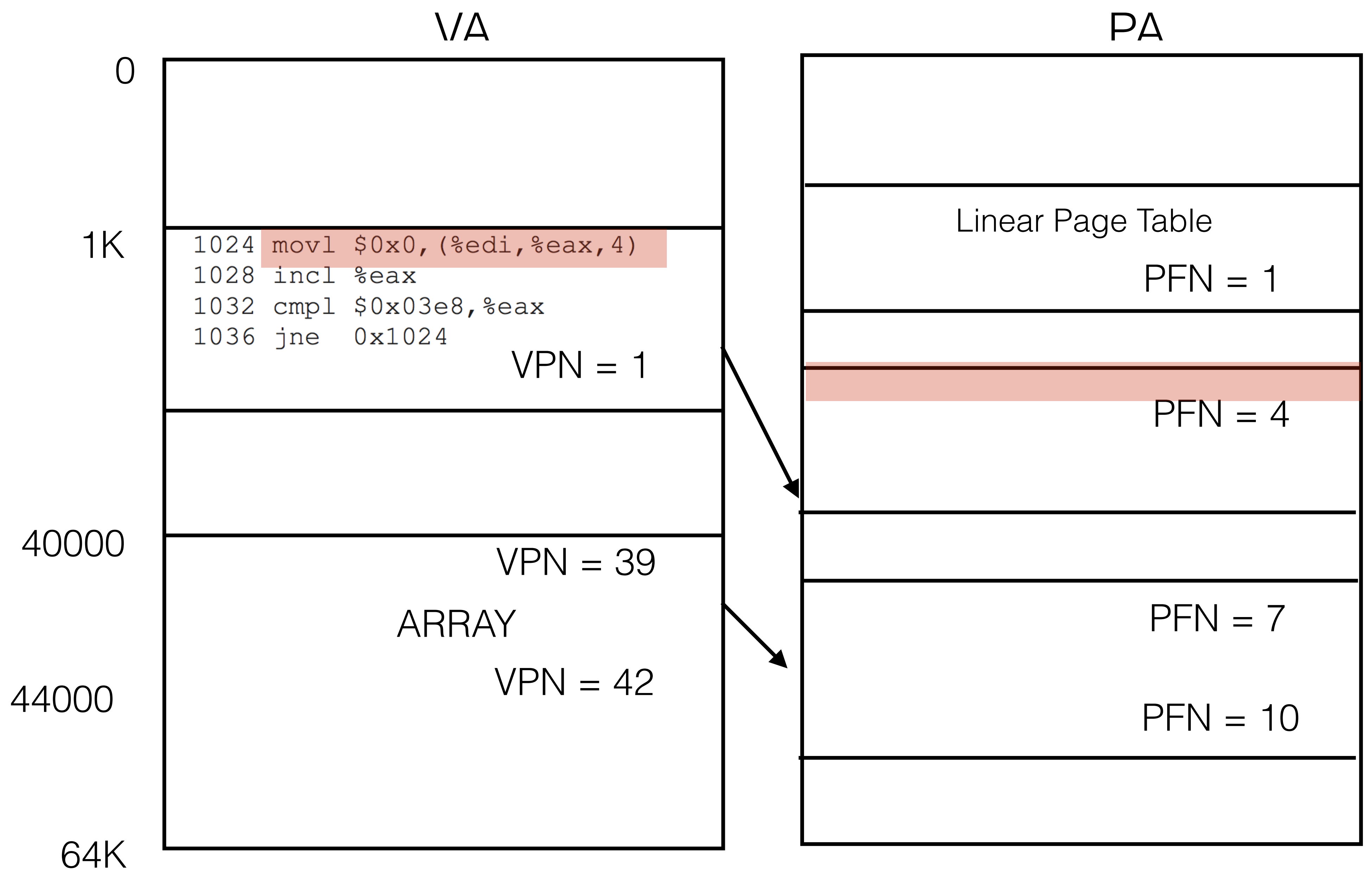
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

READ INSTRUCTION at PA(1024)

TLB

VPN	PFN
1	4



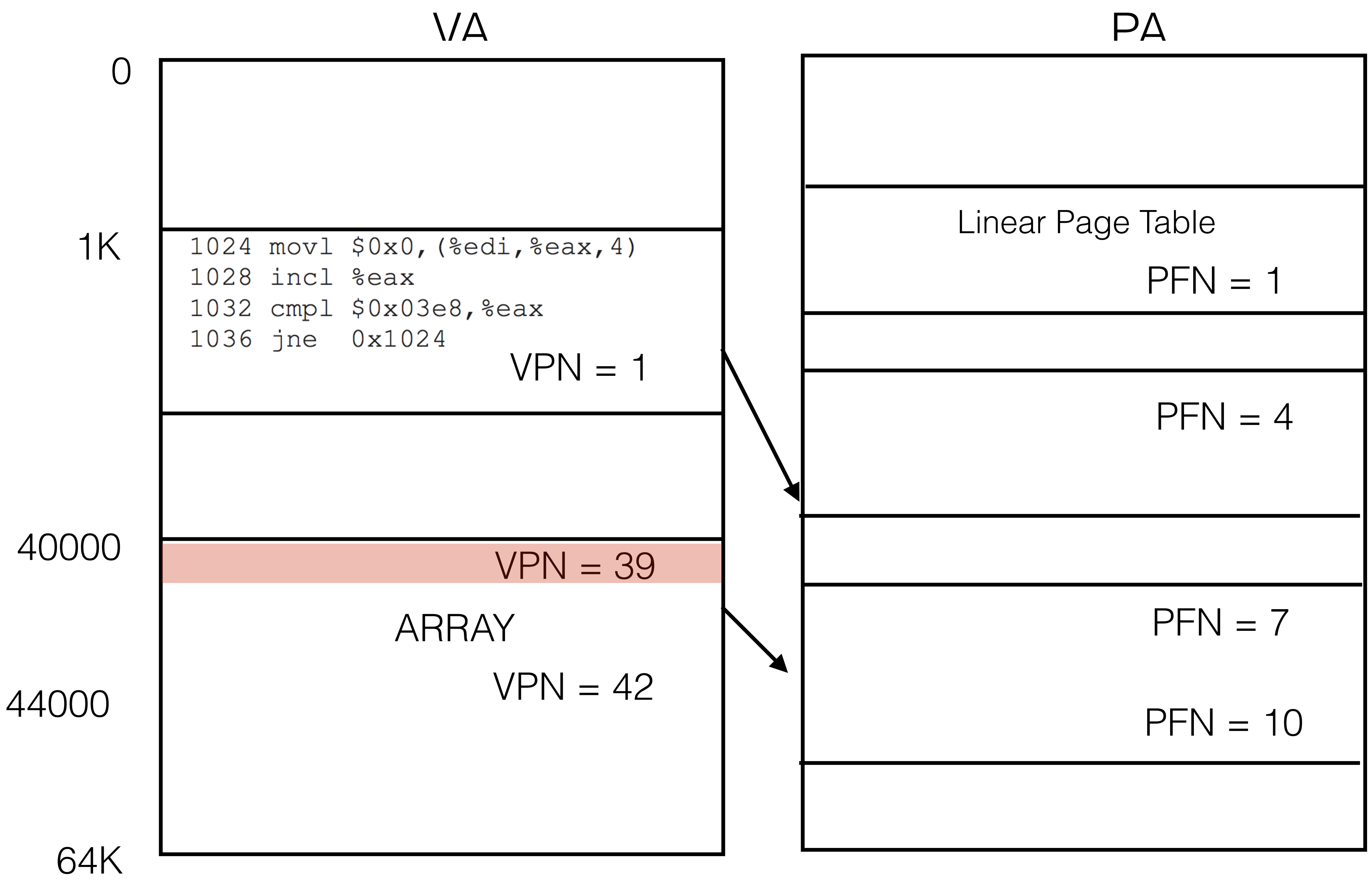
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

Find EDI + 4*EAX -> VA = 40000

TLB

VPN	PFN
1	4



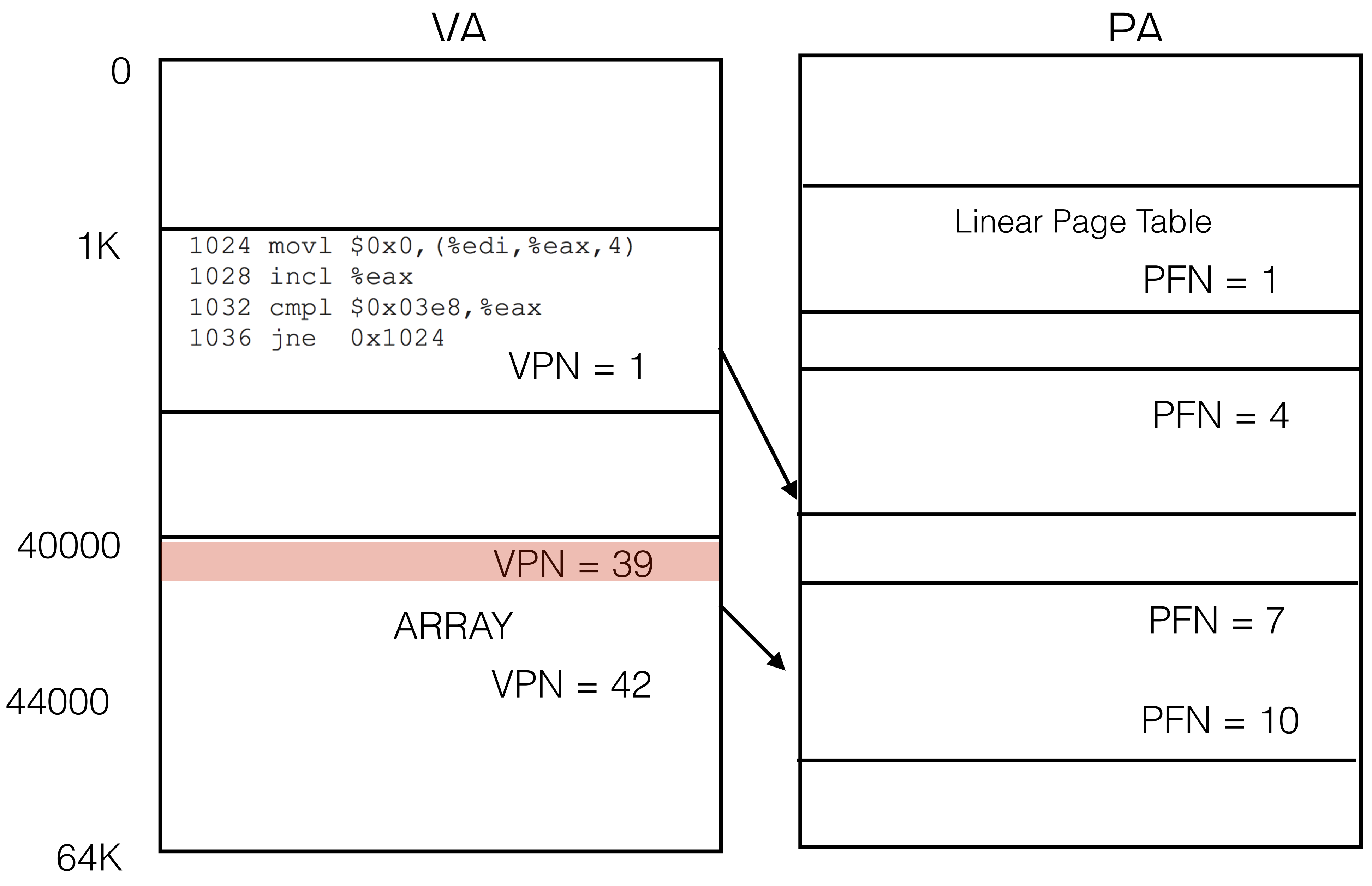
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

Find VPN for VA 40000. VPN = 39

TLB

VPN	PFN
1	4



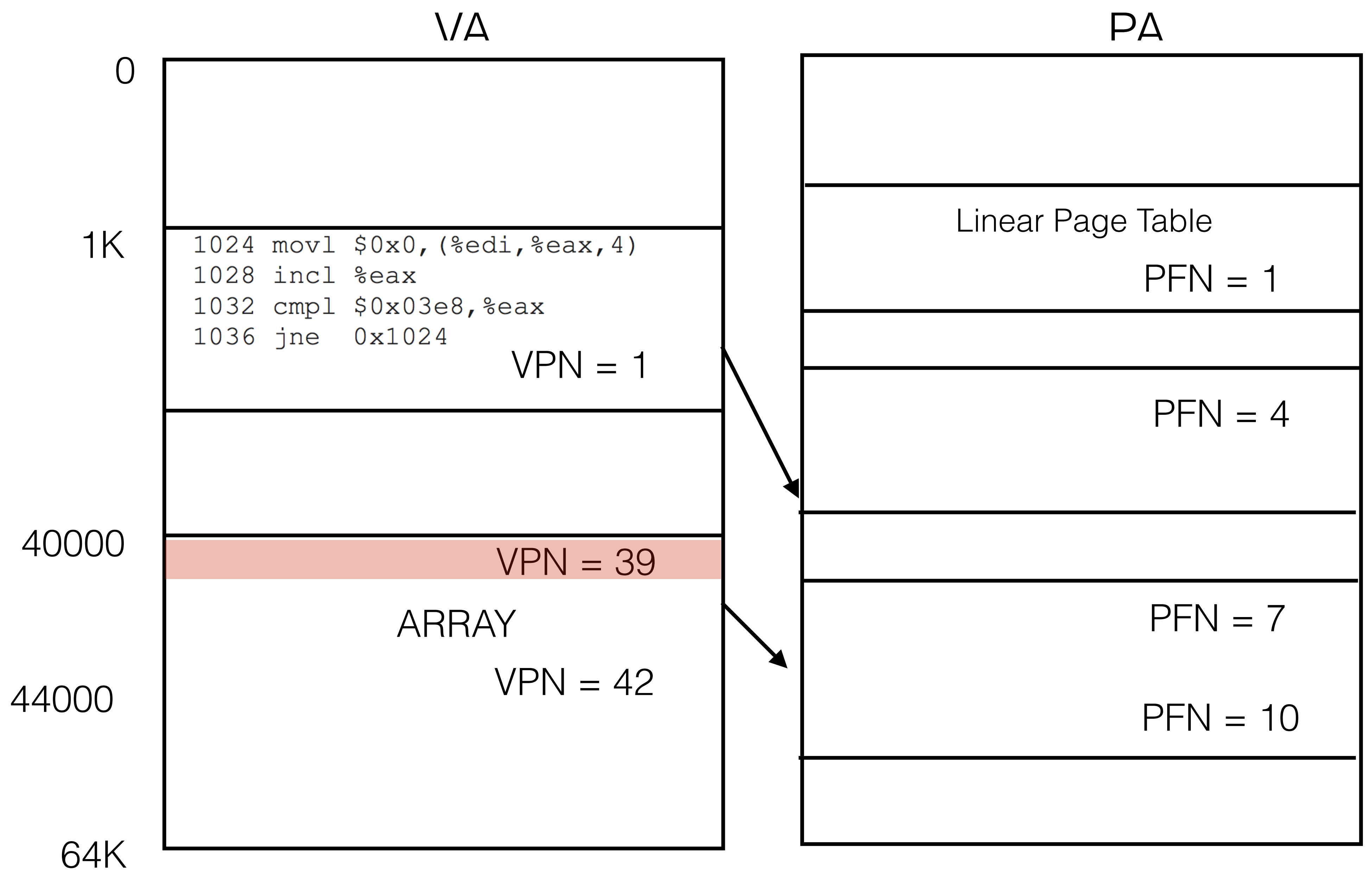
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

Check TLB for VPN = 39. Miss!

TLB

VPN	PFN
1	4



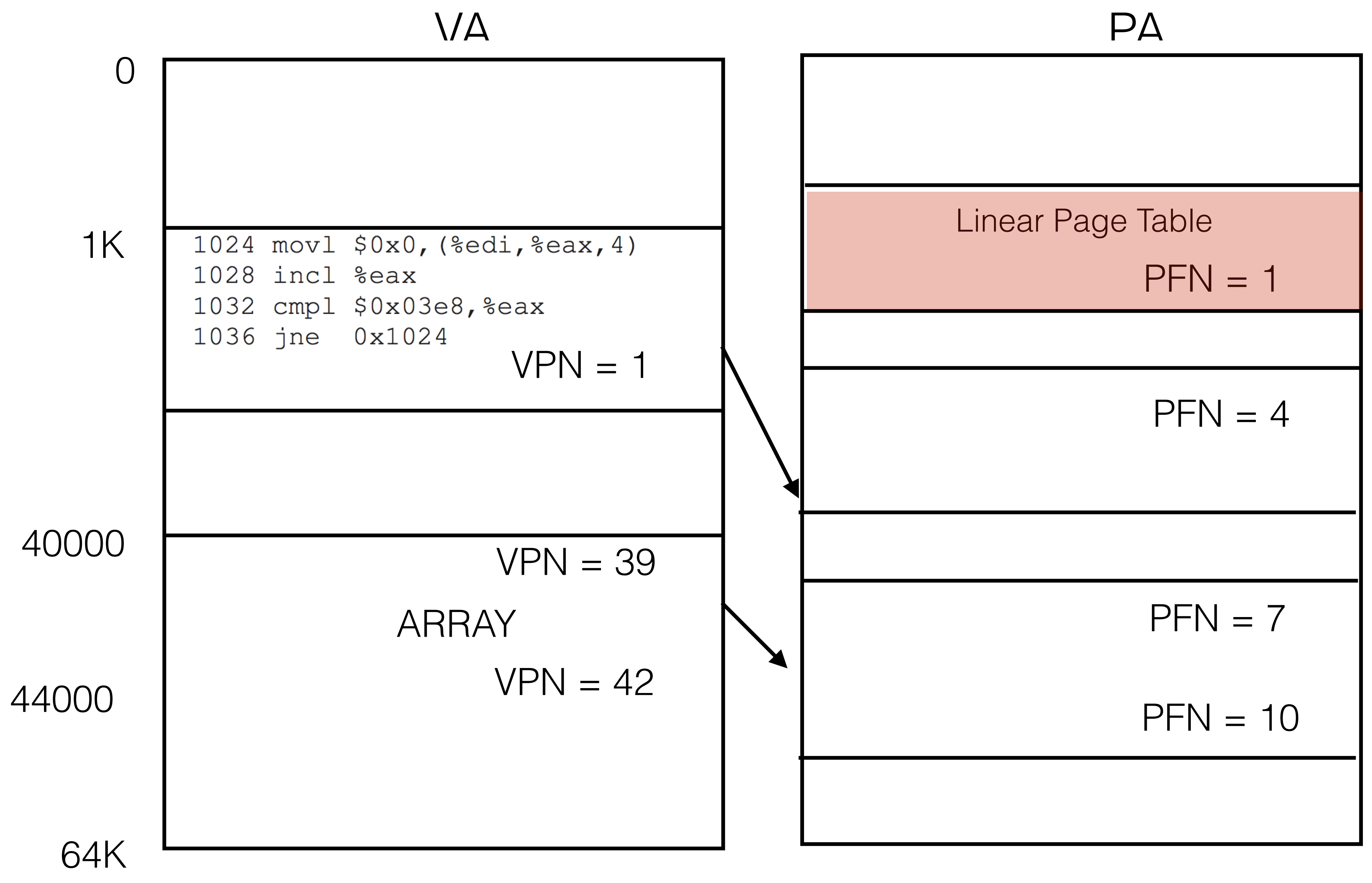
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

Get PFN for VPN = 39 from Page Table

TLB

VPN	PFN
1	4



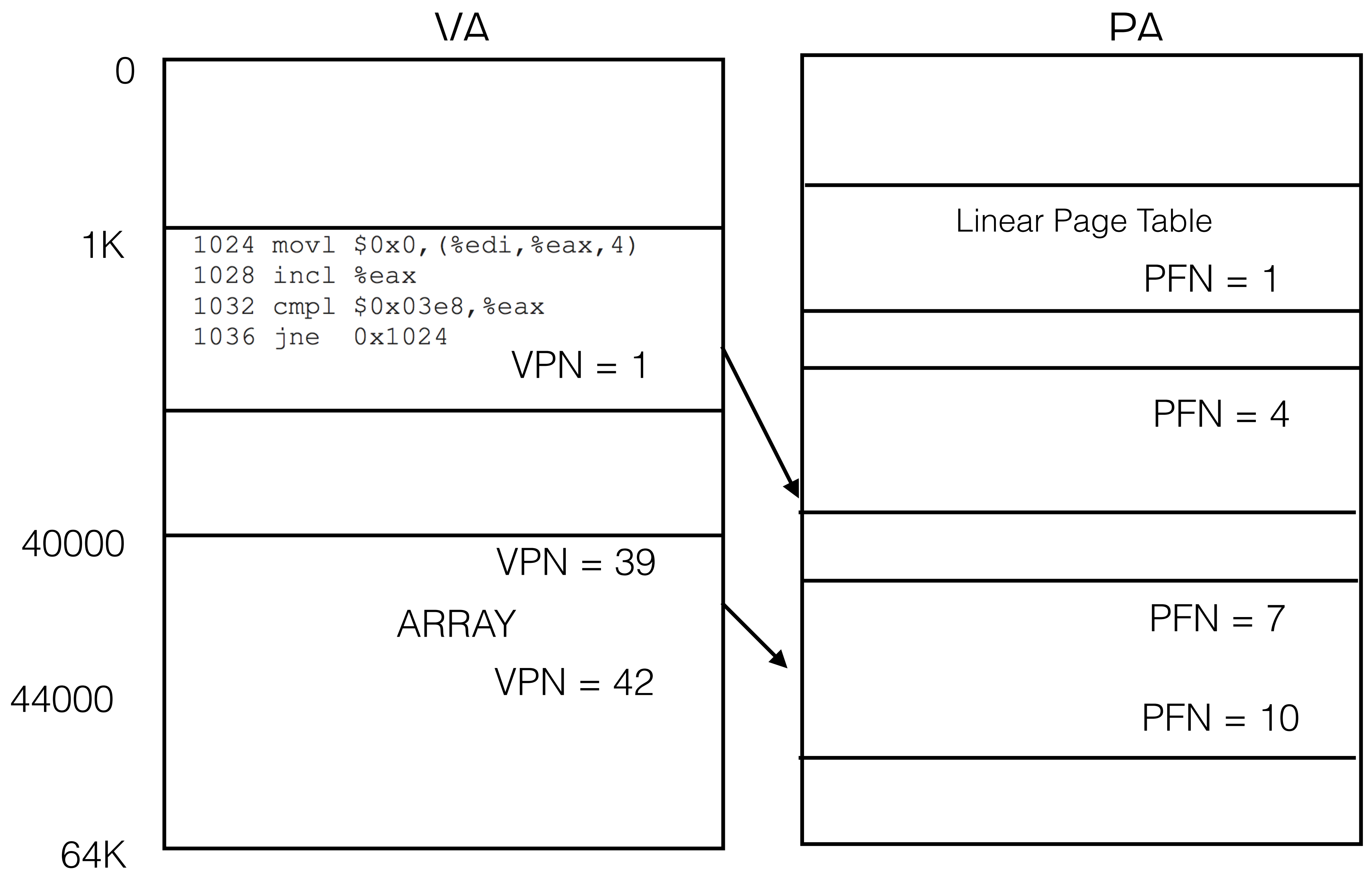
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

Store translation in TLB

TLB

VPN	PFN
1	4
39	7



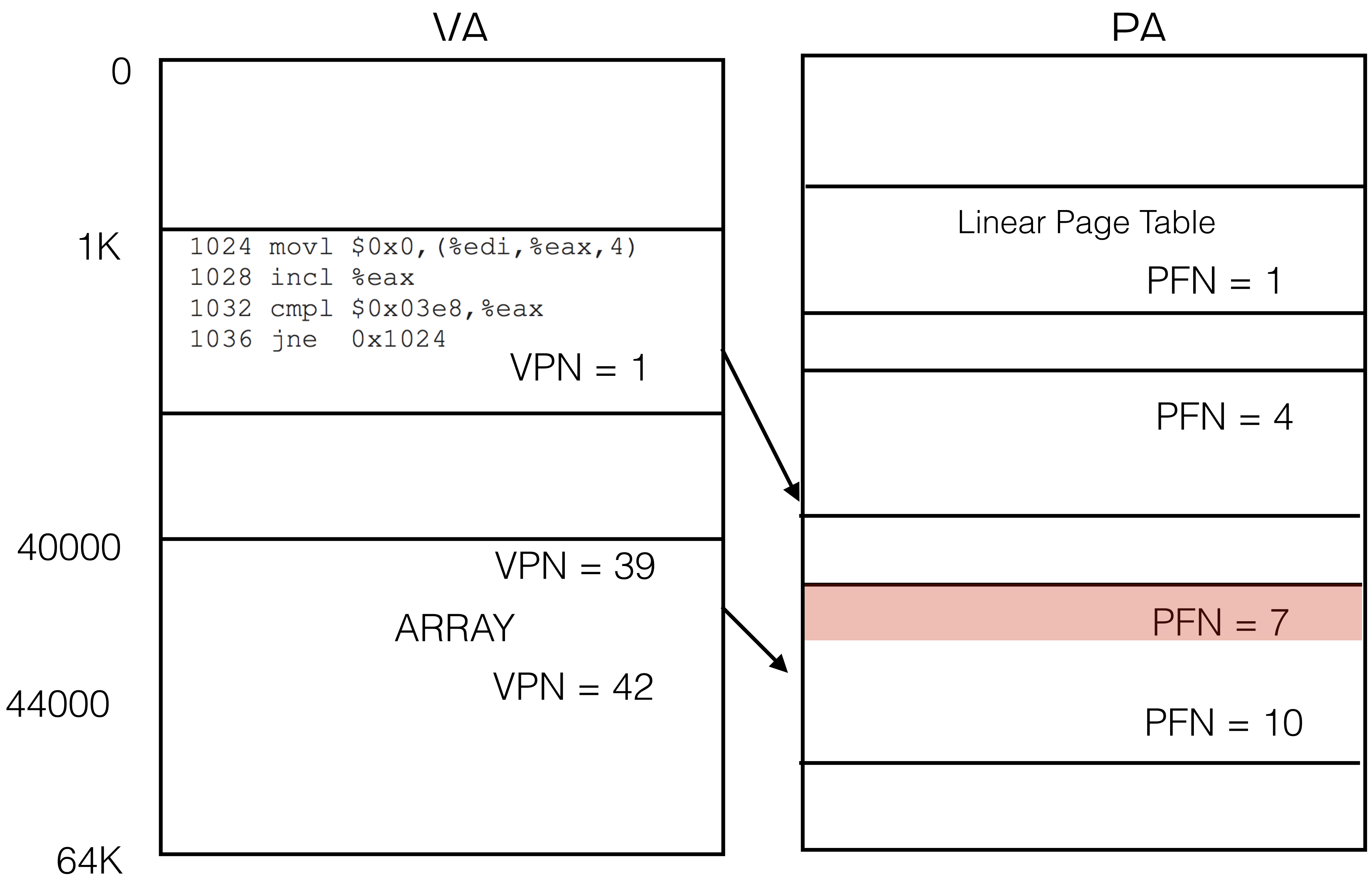
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

Find PFN of VPN = 39 from TLB. Add offset to get PA.

TLB

VPN	PFN
1	4
39	7



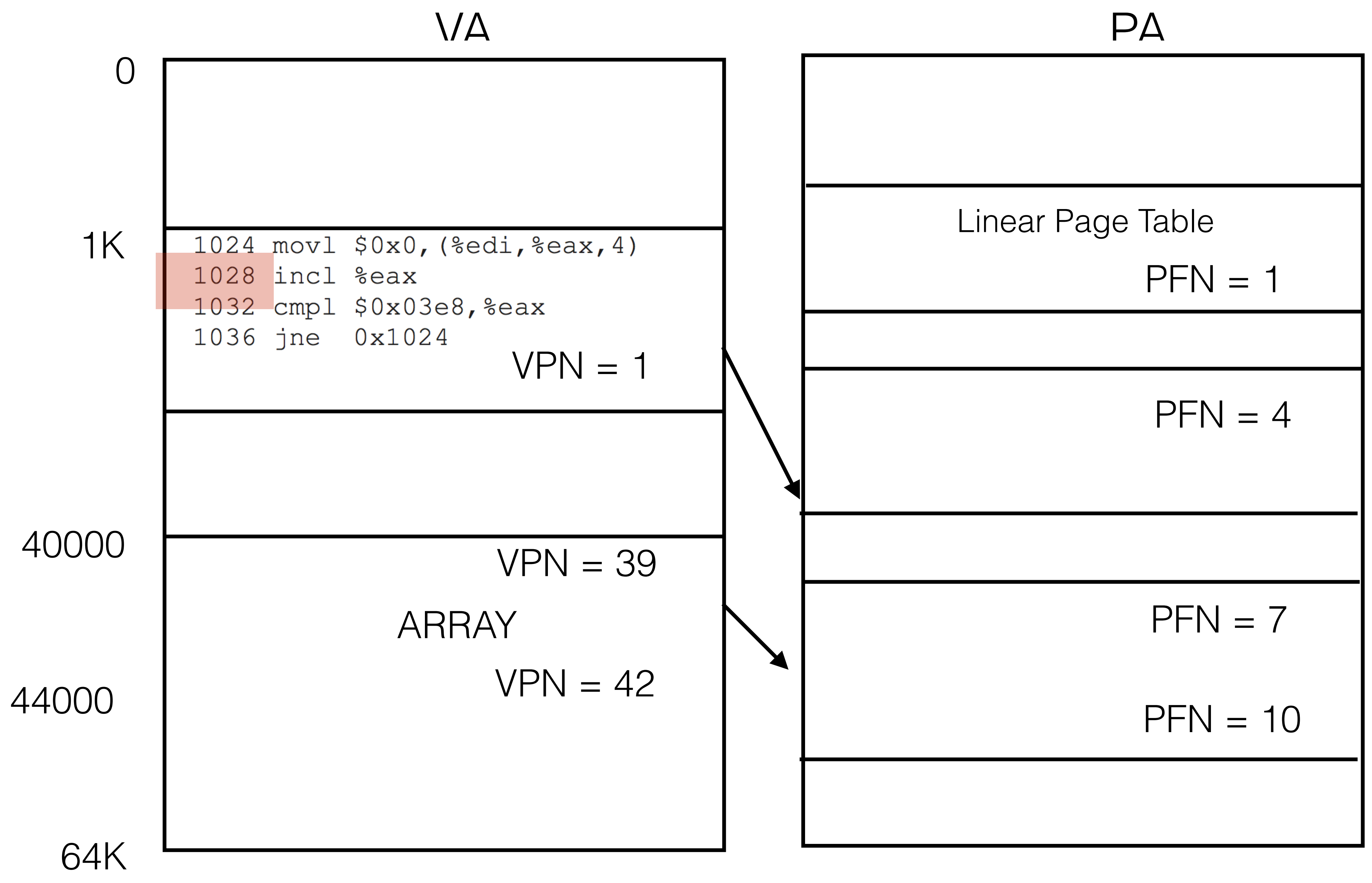
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

FIND PA FOR VA = 1028

TLB

VPN	PFN
1	4
39	7



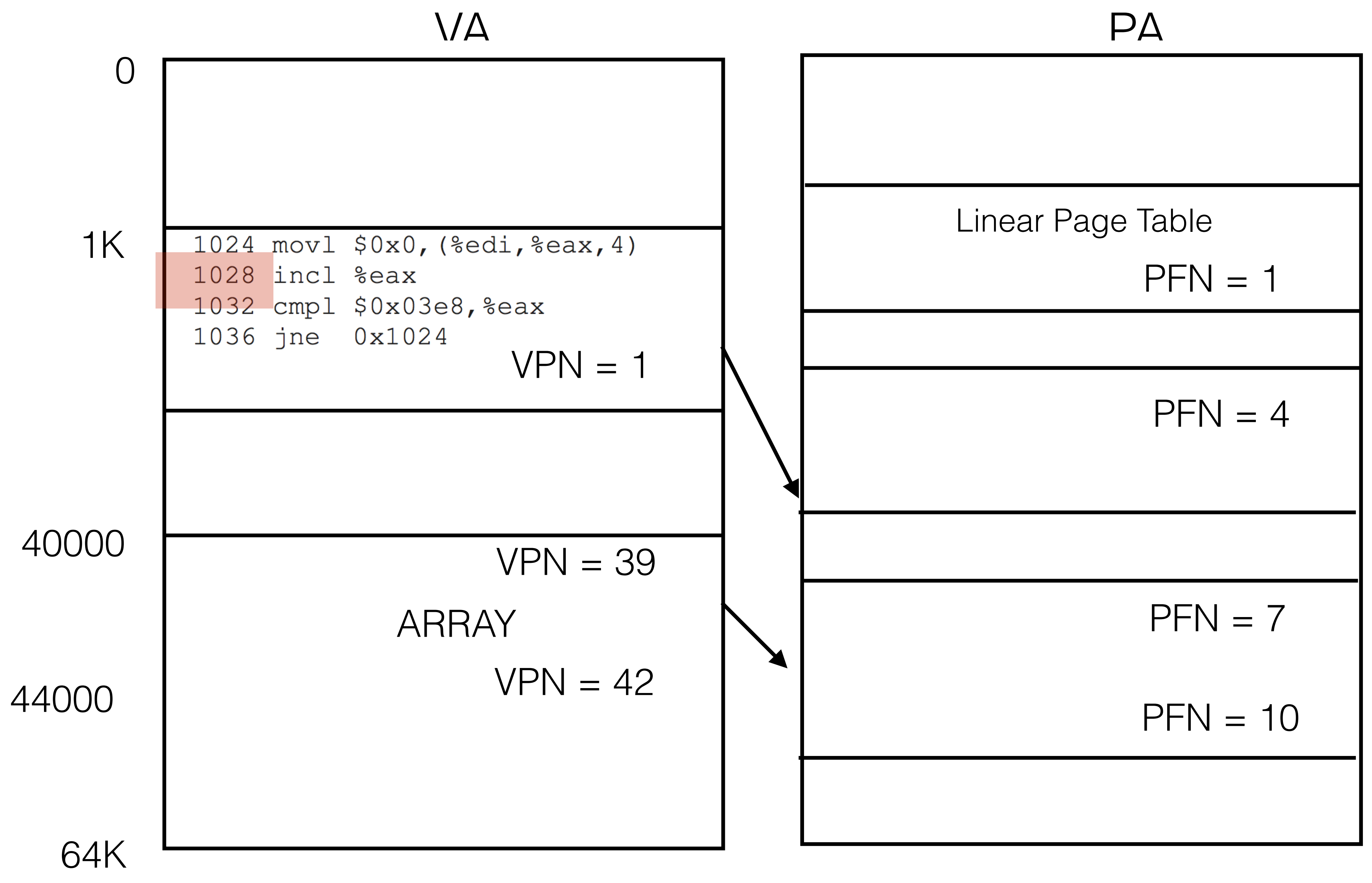
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

VPN = 1. Find Translation in TLB for VPN = 1. Found!

TLB

VPN	PFN
1	4
39	7



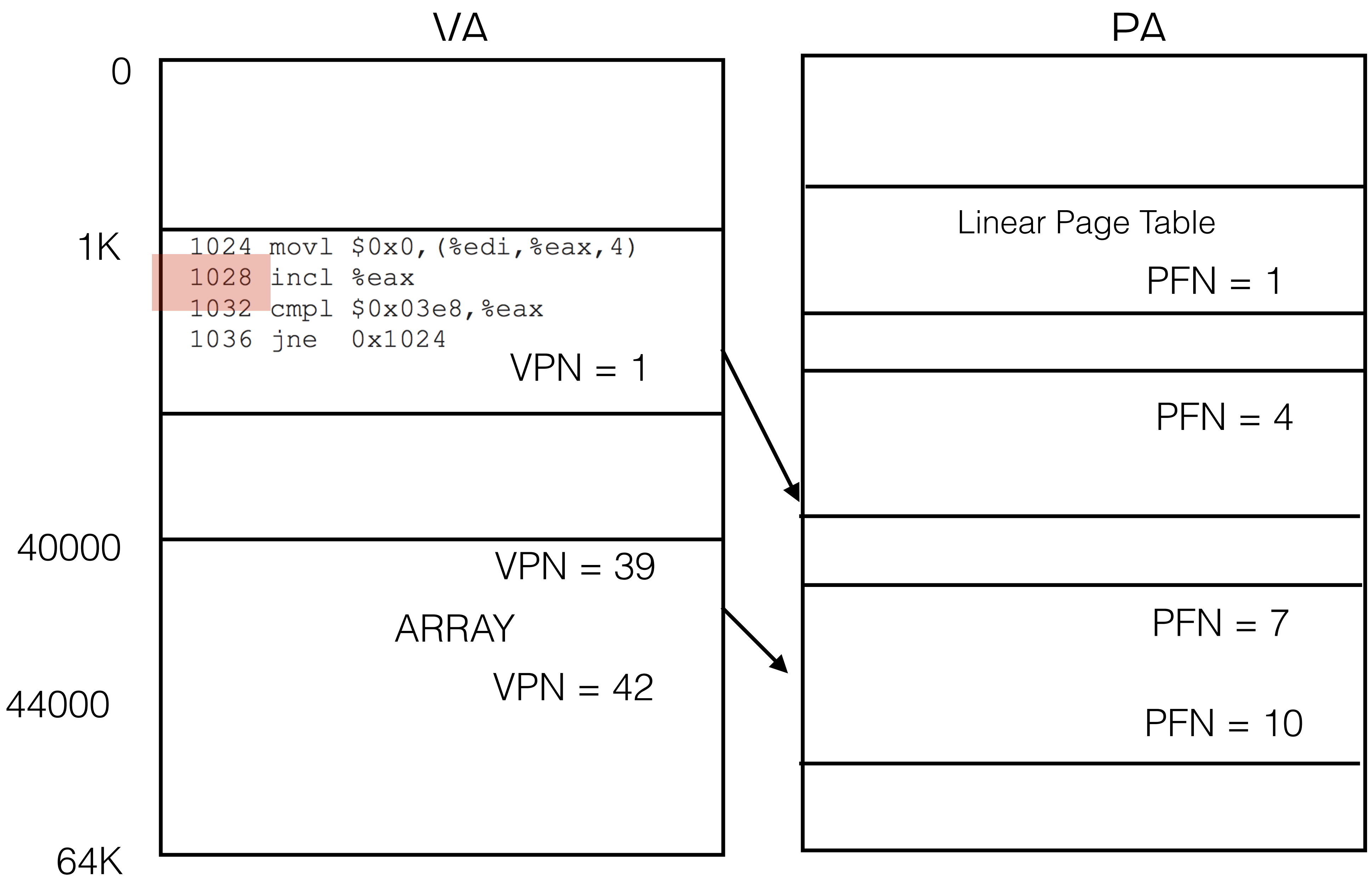
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

PFN = TLB[1] = 4

TLB

VPN	PFN
1	4
39	7



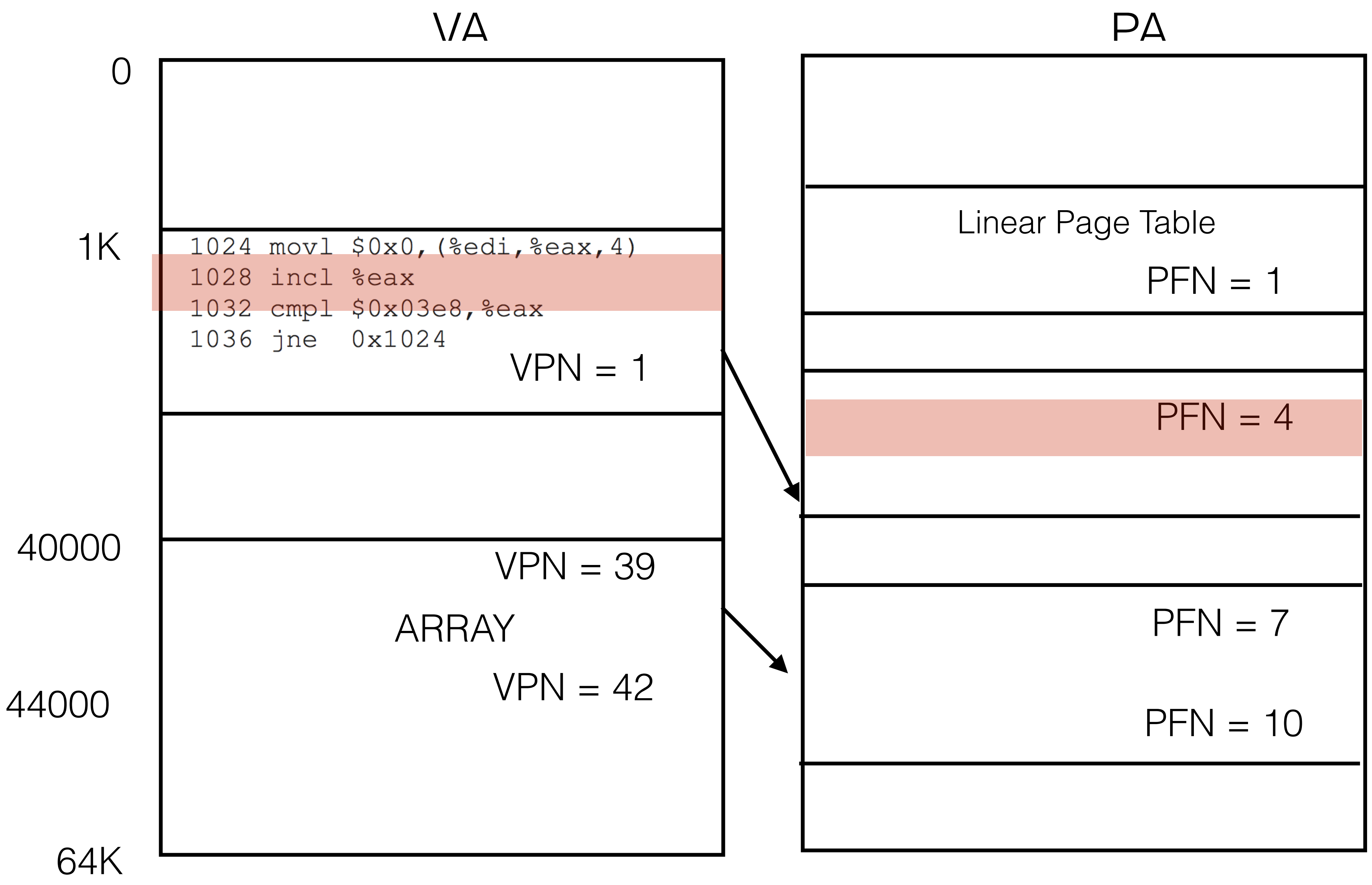
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

Get PA by adding offset to PFN = 4 and execute

TLB

VPN	PFN
1	4
39	7

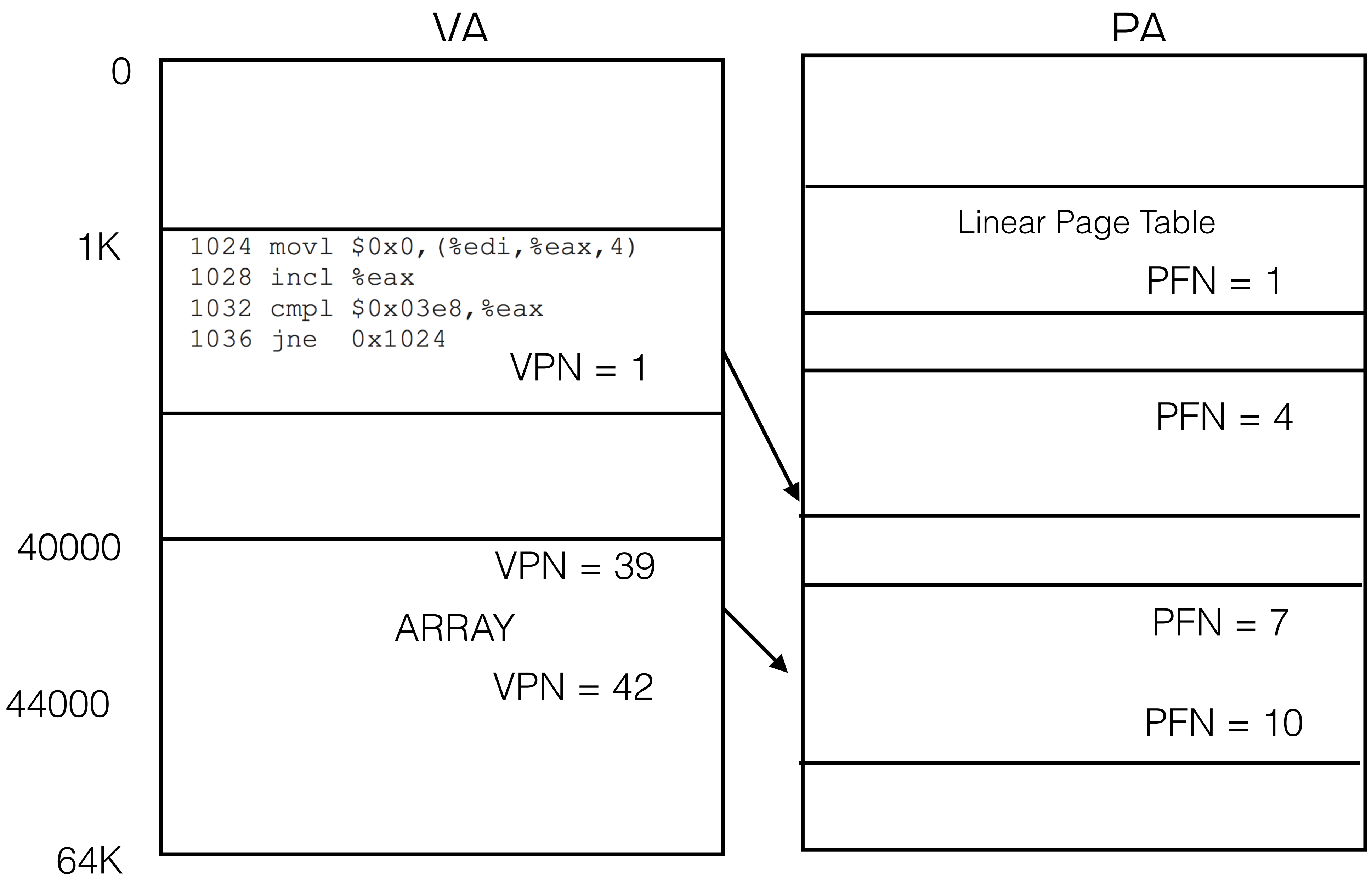


Worked Out Example

1032, 1036, 1024, 1028,…….

TLB

VPN	PFN
1	4
39	7



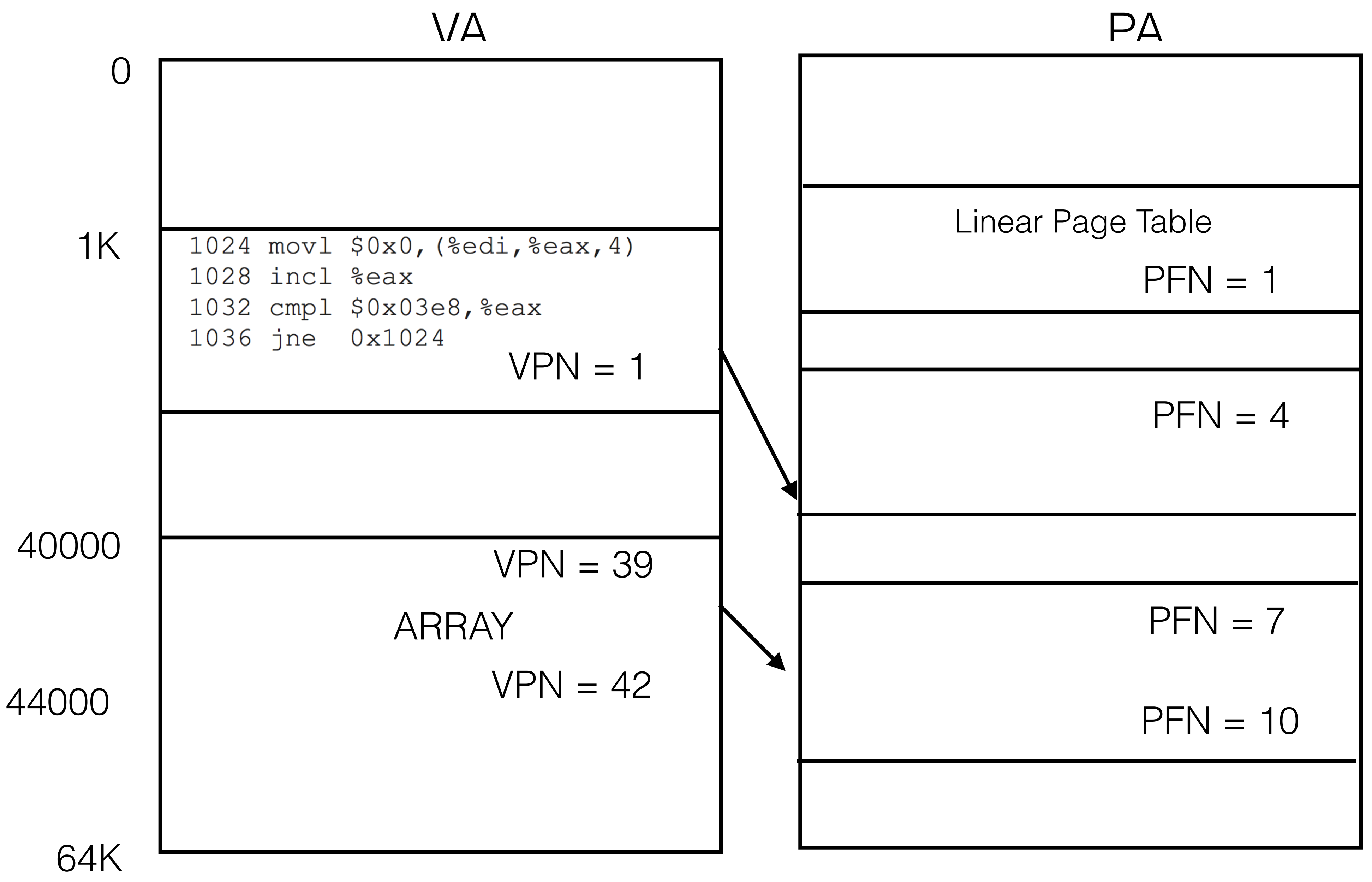
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

EDI + 4*EAX = 40000 + 4*(1024/4) = 40000 + 1K -> VPN =40

TLB

VPN	PFN
1	4
39	7



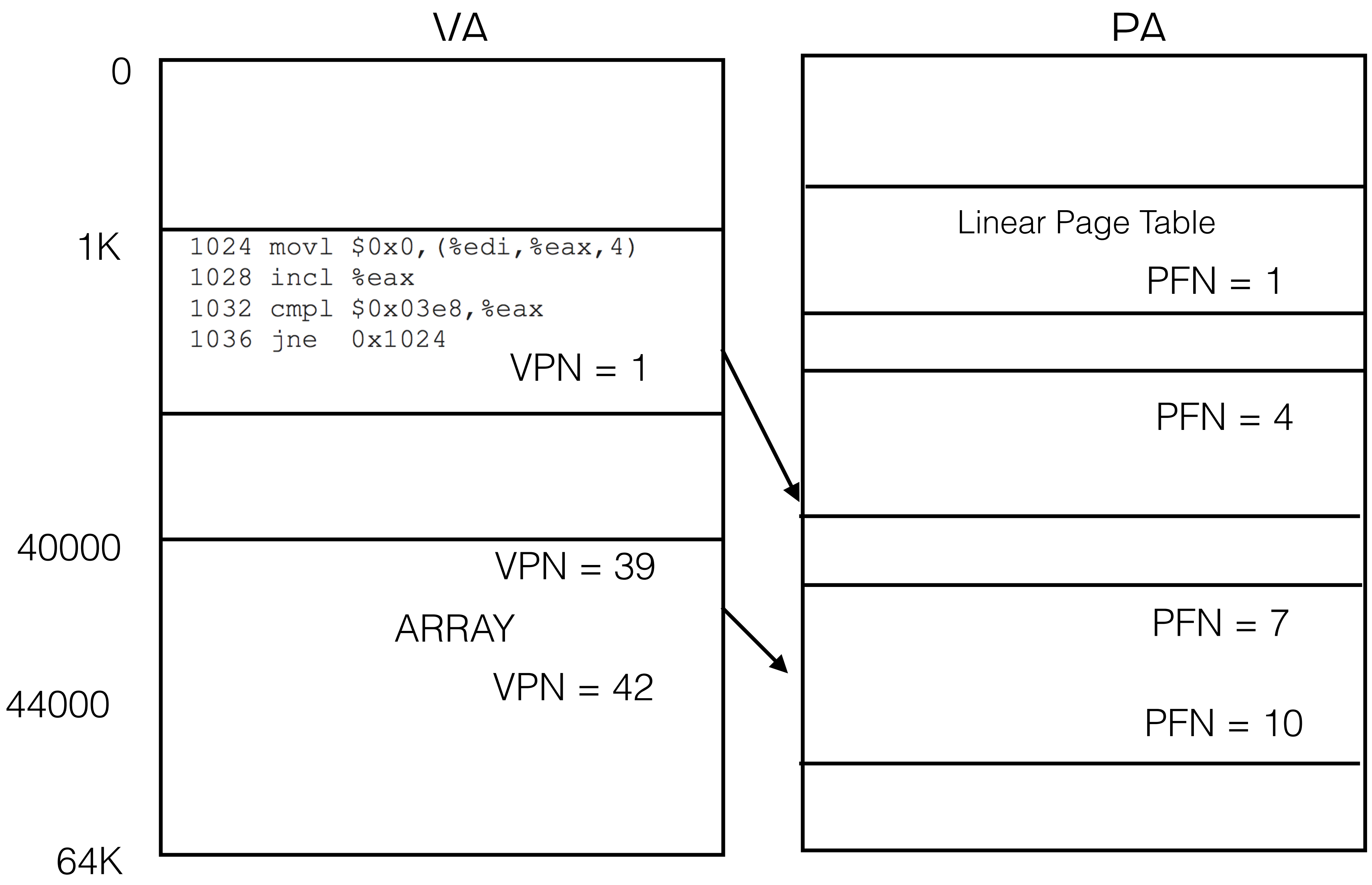
```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Worked Out Example

TLB miss for VPN = 40…

TLB

VPN	PFN
1	4
39	7



```
1024 movl $0x0,(%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne  0x1024
```

Spatial and Temporal Locality

1. Hit rate = TLB Hit/(TLB Hit + TLB Miss)
2. Spatial locality -> TLB has good hit rate
    1. Arrays elements are spatially close (EDX + 4*EAX)
    2. Instructions are spatially close (1024, …)
3. Temporal locality -> TLB has a good hit rate
    1. Loop. Re-using same instructions which exist in TLB

Memory Cycle Rate Example

1. Hit = 1 clock cycle
2. Miss = 30 clock cycles
3. Miss rate = 1%
4. Cycle rate = .99*1 + .01*(30 + 1) =1.3 cycles

Context Switch

P1 running

P2 running

TLB

VPN	PFN
1	4
39	7

Context Switch

P1 running

P2 running

TLB

VPN	PFN
1	4
39	7
…	…
1	30

What will VPN 1 be mapped to?