Multiprogramming on physical memory

- **Makes it hard to allocate space contiguously**
  - Convenient for stack, large data structures, etc.
- **Need fault isolation between processes**
  - (Even Microsoft now seems to believe this. . .)
- **Processes can consume more than available memory**
  - Dormant processes (wating for event) still have core images

Solution: Address Spaces

- **Give each program its own address space**
- **Only privileged software can manipulate mappings**
- **Isolation is natural**
  - Can't even name other processes' memory

Alternatives

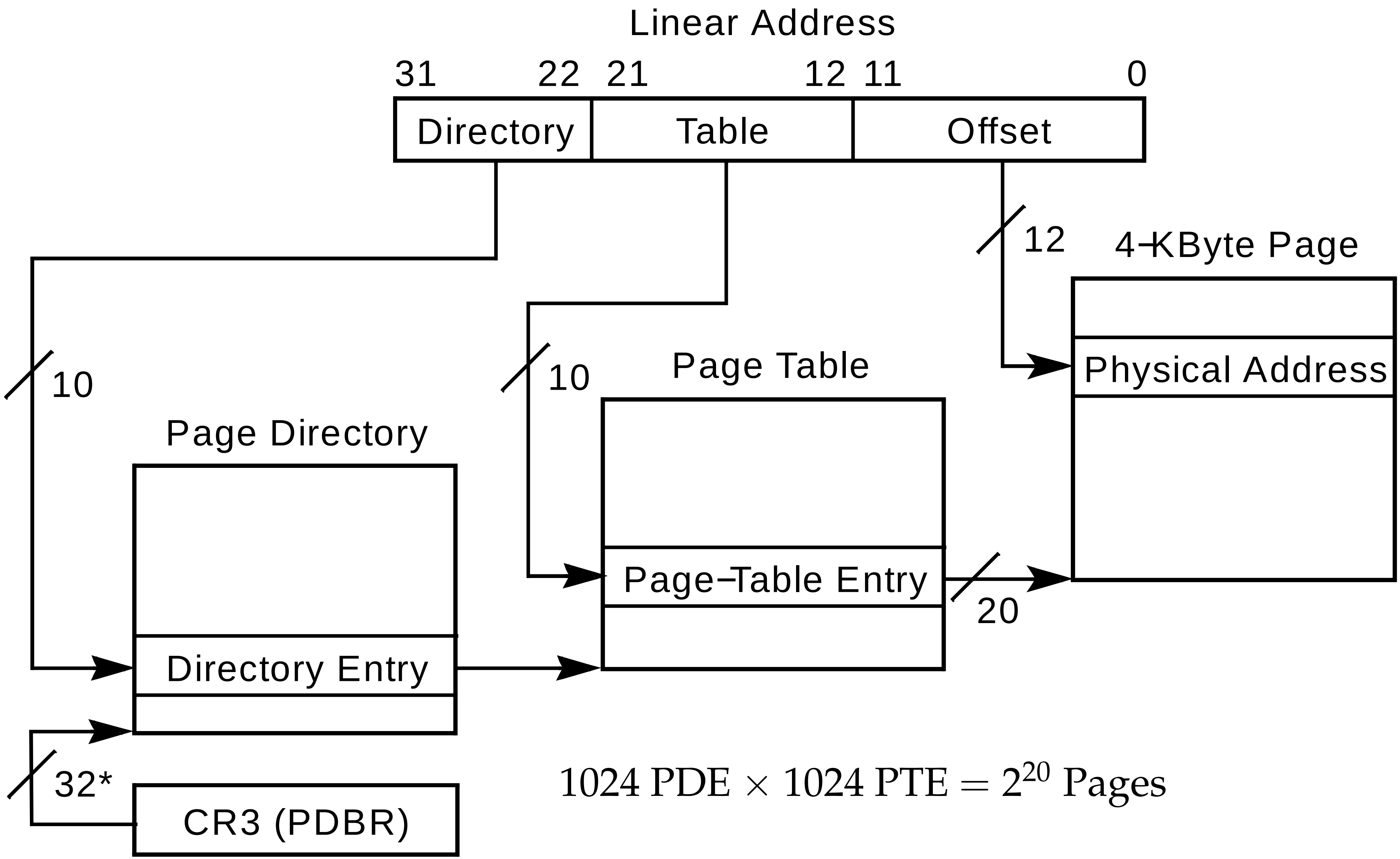
- **Segmentation**
  - Part of each memory reference implicit in segment register
    segreg $\leftarrow \langle \text{offset}, \text{limit} \rangle$
  - By loading segment register code can be relocated
  - Can enforce protection by restricting segment register loads
- **Language-level protection (Java)**
  - Single address space for different modules
  - Language enforces isolation
- **Software fault isolation**
  - Instrument compiler output
  - Checks before every store operation prevents modules from trashing each other

Paging

- **Divide memory up into small "pages"**
- **Map virtual pages to physical pages**
  - Each process has separate mapping
- **Allow OS to gain control on certain operations**
  - Read-only pages trap to OS on write
  - Invalid pages trap to OS on read or write
  - OS can change mapping and resume application
- **Other features sometimes found:**
  - Hardware can set "accessed" and "dirty" bits
  - Control page execute permission separately from read/write
  - Control caching of page

x86 Paging

- **Paging enabled by bits in a control register (`%cr0`)**
  - Only privileged OS code can manipulate control registers
- **Normally 4KB pages**
- **`%cr3`: points to 4KB page directory**
- **Page directory: 1024 PDEs (page directory entries)**
  - Each contains physical address of a page table
- **Page table: 1024 PTEs (page table entries)**
  - Each contains physical address of virtual 4K page
  - Page table covers 4 MB of Virtual mem
- **INVLPG instruction invalidates page translation**
  - Must tell hardware when page table modified

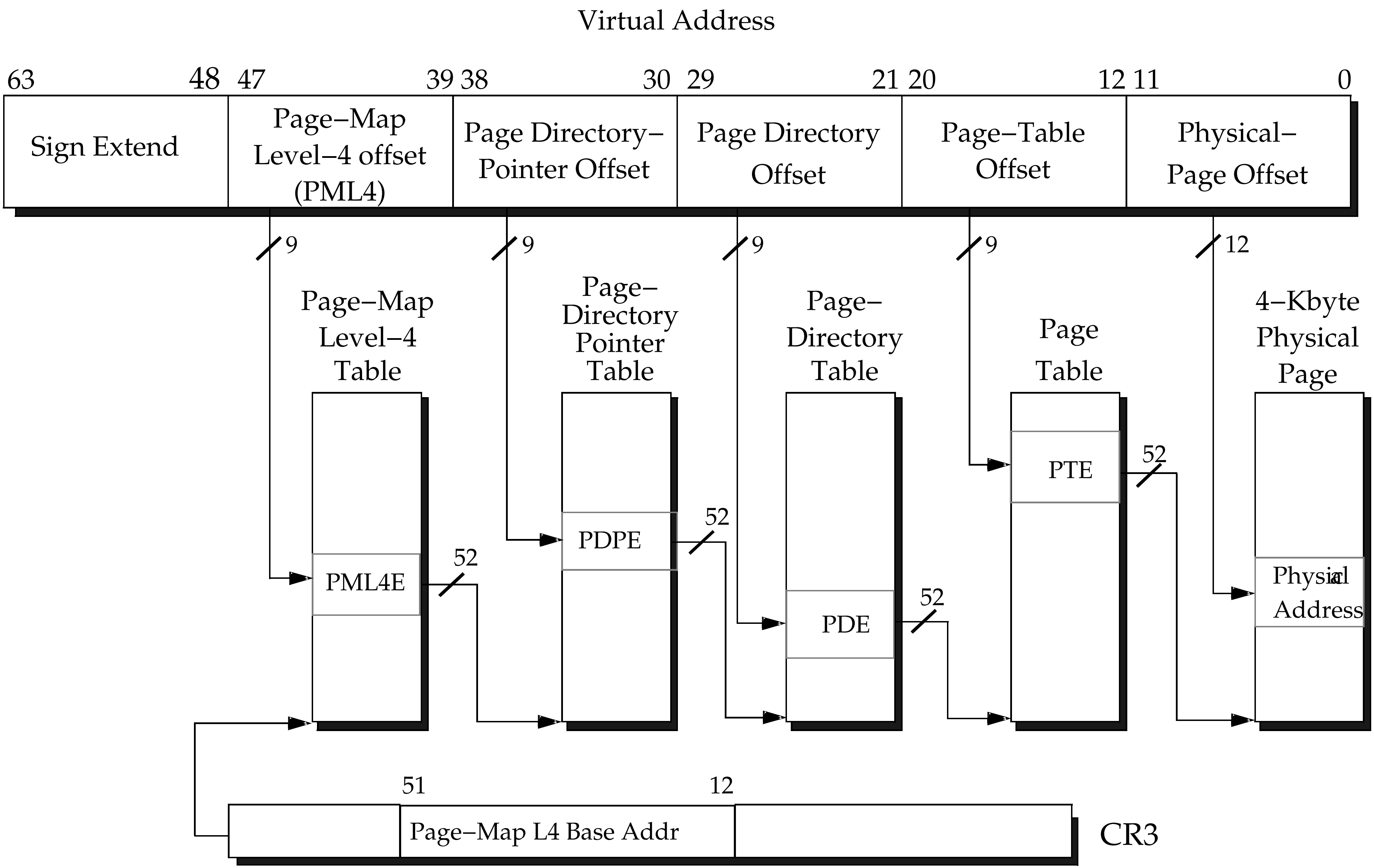


$$1024 \text{ PDE} \times 1024 \text{ PTE} = 2^{20} \text{ Pages}$$

*32 bits aligned onto a 4–KByte boundary

x86 Paging Extensions

- **PSE: Page size extensions**
  - Setting bit 7 in PDE makes a 4MB translation (no PT)
- **PAE Page address extensions**
  - New 64-bit PTE format allows 36 bits of physical address
  - Page tables, directories have only 512 entries
  - Use 4-entry Page-Directory-Pointer Table to regain 2 lost bits
  - PDE bit 7 allows 2MB translation
- **Long mode PAE**
  - In Long mode, pointers are 64-bits
  - Extends PAE to map 48 bits of virtual address



- **Why are aren't upper 16 bits of VA used?**

Very different MMU: MIPS

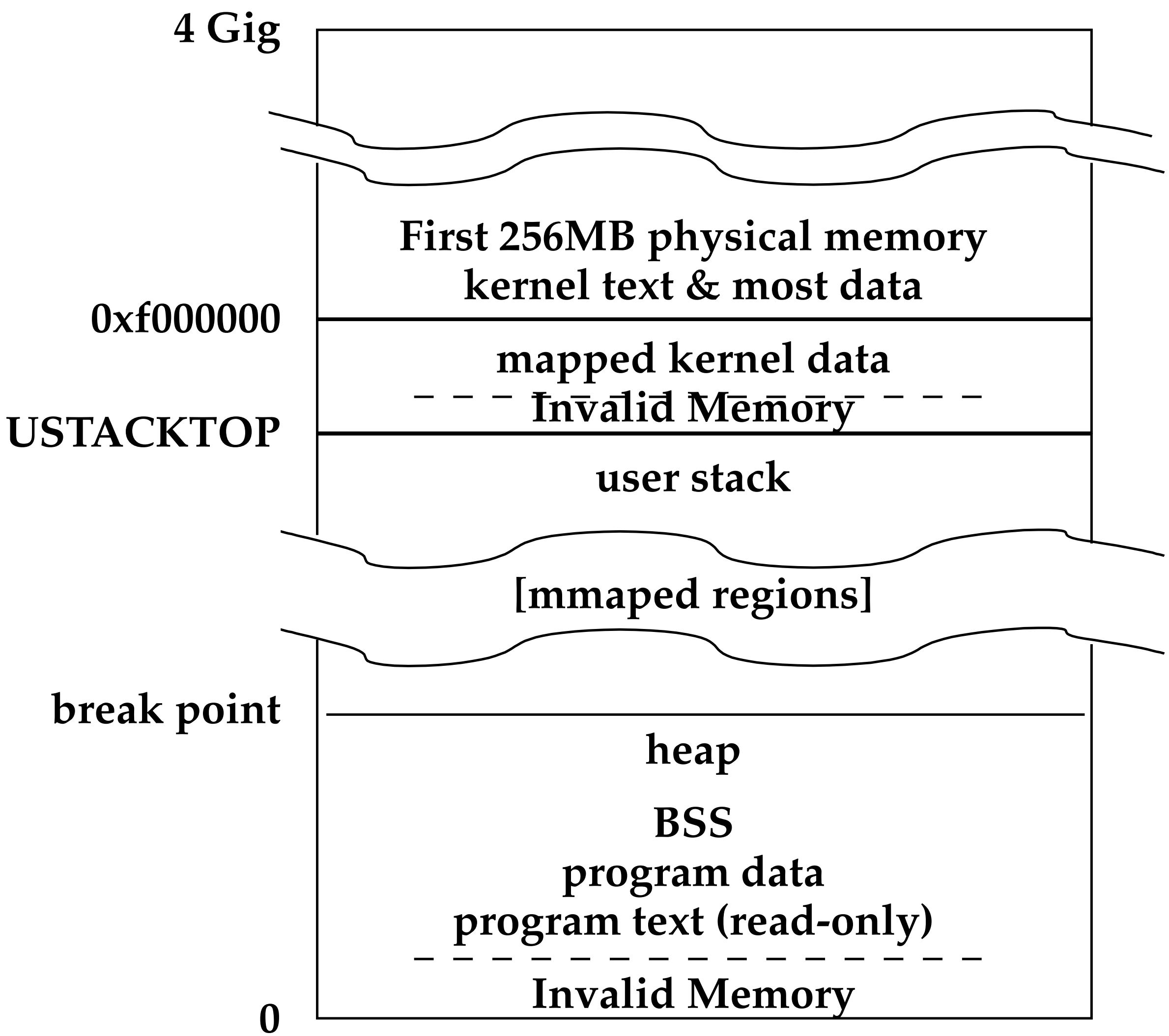
- **Hardware has 64-entry TLB**
  - References to addresses not in TLB trap to kernel
- **Each TLB entry has the following fields:**

  Virtual page, Pid, Page frame, NC, D, V, Global
- **Kernel itself unpaged**
  - All of physical memory contiguously mapped in high VM
  - Kernel uses these pseudo-physical addresses
- **User TLB fault hander very efficient**
  - Two hardware registers reserved for it
  - utlb miss handler can itself fault—allow paged page tables
- **OS is free to choose page table format!**

Paging in day-to-day use

- **Demand paging**
- **Growing the stack**
- **BSS page allocation**
- **Shared text**
- **Shared libraries**
- **Shared memory**
- **Copy-on-write (fork, mmap, etc.)**
- **Q: Which pages should have global bit set on x86?**

Example memory layout



Early VM system calls

- **OS keeps "Breakpoint" – top of heap**
  - Memory regions between breakpoint & stack fault
- `char *brk (const char *addr);`
  - Set and return new value of breakpoint
- `char *sbrk (int incr);`
  - Increment value of the breakpoint & return old value
- **Can implement** `malloc` **in terms of** `sbrk`
  - But hard to "give back" physical memory to system

More VM system calls

- `void *mmap (void *addr, size_t len, int prot, int flags, int fd, off_t offset)`
  - `prot`: OR of PROT_EXEC, PROT_READ, PROT_WRITE, PROT_NONE
  - `flags`: shared/private, …
- `int munmap(void *addr, size_t len)`
  - Removes memory-mapped object
- `int mprotect(void *addr, size_t len, int prot)`
  - Changes protection on pages to or of `PROT_`…
- `int mincore(void *addr, size_t len, char *vec)`
  - Returns in `vec` which pages present

Catching page faults

```
struct sigaction {
  union {                     /* signal handler */
    void (*sa_handler)(int);
    void (*sa_sigaction)(int, siginfo_t *, void *);
  };
  sigset_t sa_mask;           /* signal mask to apply */
  int sa_flags;
};

int sigaction (int sig, const struct sigaction *act,
               struct sigaction *oact)
```

- **Can specify function to run on** `SIGSEGV`

Example: OpenBSD/i386 siginfo

```
struct  sigcontext {
  int sc_gs; int sc_fs; int sc_es; int sc_ds;
  int sc_edi; int sc_esi; int sc_ebp; int sc_ebx;
  int sc_edx; int sc_ecx; int sc_eax;

  int sc_eip; int sc_cs; /* instruction pointer */
  int sc_eflags;         /* condition codes, etc. */
  int sc_esp; int sc_ss; /* stack pointer */

  int sc_onstack;   /* sigstack state to restore */
  int sc_mask;      /* signal mask to restore */

  int sc_trapno;
  int sc_err;
};
```