Virtual memory - Paging

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The process

Memory layout for a 32-bit Linux process

Segments - a could be solution

one problem

External fragmentation: free areas of free space that is hard to utilize.

Solution: allocate larger segments ... internal fragmentation.
Let's try again

It's easier to handle fixed size memory blocks.

Can we map a process virtual space to a set of equal size blocks?

An address is interpreted as a *virtual page number* (VPN) and an *offset*.
The x86-32 architecture supports both segmentation and paging. A virtual address is translated to a *linear address* using a segmentation table. The linear address is then translated to a physical address by paging.

Linux and Windows do not use segmentation to separate code, data nor stack.

The X86-64 (the 64-bit version of the x86 architecture) has dropped many features for segmentation.

Still used to manage *thread local storage* and *CPU specific data*.
The page table

The page table
- provides translation from page numbers to frame numbers
- kernel or user space
- read and write access rights
- available in memory or on disk

Note: the page table is to large to fit into the MMU hardware, it is in main memory.

Physical Address Extension (PAE)

In 1995 the x86 architecture provided 24-bit frame numbers. The CPU could thus address 64 Gbyte of physical address space (24-bit frame, 12-bit offset).

Each process still had a 32-bit virtual address space, (20-bit page number, 12-bit offset) i.e. 4 Gbyte.

The x86_64 architecture supports 48-bit virtual address space and up to 52-bit physical address space.

Linux supports 48-bit virtual address (47-bit user space) and up to 46-bit physical address space (64 Tbyte). Check your address space in /proc/cpuinfo.

Physical memory is in reality limited by chipset, motherboard, memory modules etc. Check your available memory in /proc/meminfo.

largest server

Largest server on the market, SGI 3000, can scale up to 256 CPUs and 64 Tbyte of RAM (NUMA) - running Linux.
Speed matters

- we need a page table base register, PTBR
- the virtual page number, VPN, is 0x11111
- read the page table entry from PTBR + (0x11111 * 8)
- extract frame number, PFN from the entry
- the offset is 0x222
- read the memory location at (PFN << 12) + 0x222

An extra memory operation for each memory reference.

TLB: hardware support

The CPU keeps a translation look-aside buffer, TLB, with the most recent page table entries.

- The buffer is implemented using a content-addressable memory keyed by the virtual page number.

If the page table entry is found - great!

If the page table entry is not found - access the real page table in memory.

Who handles a TLB miss

RISC architecture
- MIPS, Sparc, ARM
- The hardware rises an interrupt.
- The operating system jumps to a trap handler.
- The operating system will access the TLB and update the TLB.

CISC architecture
- x86
- The hardware "knows" where to find the page table (CR3 register).
- The hardware will access the page table and updates the TLB.

Process switching

What happens when we switch process?

- The TLB contains the cached translations of the running process, when switching process the TLB must (in general) be flushed.

Do we have to flush the whole TLB?

Is this best handled by the hardware or operating system?

Can we do pre-fetching of page table entries?
The paging MMU with TLB

virtual addr.\[\leftarrow\rightarrow\]
offset

VPN
TLB
PFN

physical address

VPN
PTBR

Page table in memory

Size matters

Using 4 Kibyte pages (12 bits) for a 4 Gibyte address space (32 bits) will result in 1Mi (20 bits) page table entries.

Each page table entry is 4 bytes.

A page table has the size of 4 Mibyte.

Each process has its own page table.

For 100 processes we need room for 400 Mibyte of page tables.

Problem!

The solution - not.

Why not use pages of size 4 Mibyte?

- Use a 22 bit offset and 10 bit virtual page number.
- Page table 4 Kibyte (1024 entries, 4 byte each).
- Case closed!

4 Mibyte pages are used and do have advantages but it is not a general solution.

Mostly empty space

Map only the areas that are actually used.
Hybrid approach - paged segmented memory

What if each segment was rarely larger than 1Ki pages of 4Kibyte.

<table>
<thead>
<tr>
<th>seg</th>
<th>18-bit page number</th>
<th>12-bit offset</th>
</tr>
</thead>
</table>

base/bound

page table

frame number

page

Multi-level page table

<table>
<thead>
<tr>
<th>31</th>
<th>22</th>
<th>12</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-bit directory index</td>
<td>10-bit page index</td>
<td>12-bit offset</td>
<td></td>
</tr>
</tbody>
</table>

Used by Intel 80386

Mostly empty space

Each page table can map 4 Mibyte

virtual address space

More than two levels

<table>
<thead>
<tr>
<th>31</th>
<th>29</th>
<th>2120</th>
<th>12</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-bit offset</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

9-bit page table index

2-bit page global directory index

Scheme used in PAE, where each entry has a 24-bit physical base address. Each page table entry was 8 bytes wide.

Trace the translation of a 32-bit virtual address to a 36-bit physical address.
The x86_64 architectures

- A 64-bit address but only 48-bits are used.
- Bits 63-47 are either 1, kernel space, or 0, user space.
- The 48 bits are divided into:
  - 9-bit page global directory index
  - 9-bit page upper directory index
  - 9-bit page lower directory index
  - 9-bit page table index
  - 12-bit offset
- A page table entry is 8 bytes and contains a 40-bit physical address base address.
- The 40-bit base is combined with the 12-bit index to a 52-bit physical address.

Linux can only handle a physical base address of 34 bits i.e. 46 bit physical address.

Summary

- Segmentation is not an ideal solution (why?).
- Small fixed size pages is a solution.
- Speed of translation is a problem (what is the solution?)
- The size of the page table is a problem (and you know how to solve it).
- Inverted page tables - an alternative approach.

Inverted page tables

Why not do something completely different?

- We will probably not have more than say 8 Gbyte of main memory.
- If we divide this into 4 Kibyte frames we have 2 Mi frames.
- Assume maintain a table with 2 Mi entries that describes which process and page that occupies the frame.
- To translating a virtual address we simply search the table (efficient if we use a hash table).
- Used by some models of PowerPC, Ultra Sparc and Itanium.

AC/DC - TLB

TLB - dynamite, makes paging possible.