## Virtual Memory in PeANUt

- ref: [PeANUt Spec, sect 3]; additionally [O'H&Bryant, sect 10.1–10.7] or [Null&Lobur, sect 6.5]
- virtual memory implementation
  - page tables
- virtual memory in PeANUt
  - page replacement
  - paging behaviour
  - working sets
- other issues:
  - redeemable MSE confirmed!
  - TuteLab08 Handout - preparation!

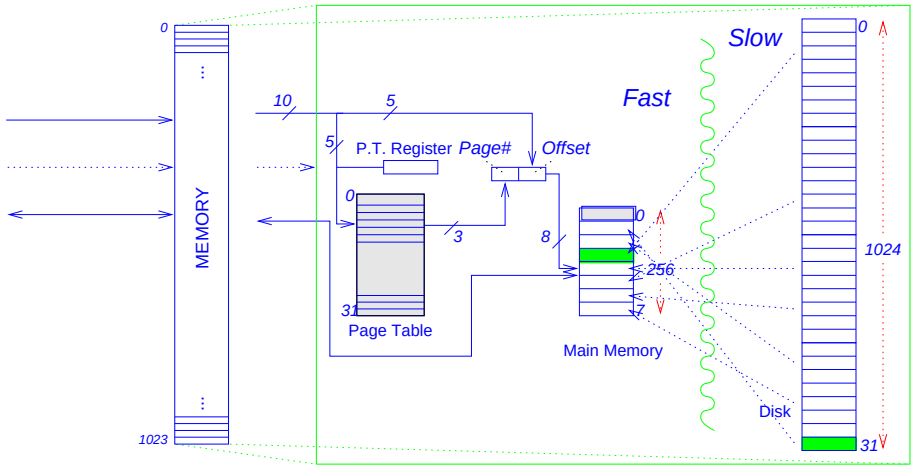


## Virtual Memory in PeANUt

- our previous model of the PeANUt considered memory to be a *black box*
  - data was written or read by the memory automatically
  - suppose paging is implemented: how would you know if the data is in main memory or on the disk?
- a closer look at PeANUt memory:
  - main memory (MM): 256 cells, in 8 × 32-cell page frames
  - secondary memory (SM): 1024 cells, in 32 × 32-cell pages
- VM is controlled by a Memory Management Unit (MMU)
  - not explicitly shown in PeANUt architecture
  - uses a page table with 32 entries (one per page)
  - translates virtual addresses into physical addresses
  - moves pages between main memory and disk whenever necessary



## The PeANUt Virtual Memory System






## Page Tables

- purpose: give information on the status of each of the pages of the virtual memory
  - is it present in main memory? Present bit
  - if so, in which page frame is it? Frame number field (3 bits)
  - if so, has data been written to it? Dirty bit

| Other information | D | P | Frame |
|---|---|---|---|

- where does this page table reside?
  - possibly in special hardware
  - in PeANUt: part of main memory, at VM addresses 0–31 (large: 1/8 of main memory!)

## How Does PeANUt Virtual Memory Work?

- to read some data (at say address `00101 01010`)
  1. the address is split into two parts: a page number (`00101`) and a page offset (`01010`)
  2. the status of the page is checked with the page table:

| Other information | D | P | Frame |
|---|---|---|---|

  3. A) if page is in main memory (P is set):
     - lookup its page frame number (say page frame 3 (`011`))

     B) otherwise, a page fault occurs:
     - fetch page from secondary memory into main memory, possibly removing another page
     - find the new page frame number of the page
  4. combine page frame number with the page offset to produce an 8 bit address (`011 01010`), giving the location of the cell in main memory
- to write some data: almost the same procedure as above

  (must also set the dirty bit (D) in the page table)



## Page Replacement

- how do we decide which page to throw out?
- Random: cannot get any performance advantages from locality of reference
- First In First Out (FIFO):
  - hardware/OS keeps track of age of each page
  - replace the oldest page
  - problem: any page continuously required must eventually be thrown out!
- Least Recently Used (LRU):
  - hardware keeps track of access times to each page
  - replace the least recently used page
  - generally performs quite well



## Paging Policy Failure

- example: access pages 0, 1, 2, 3, 4 cyclically:

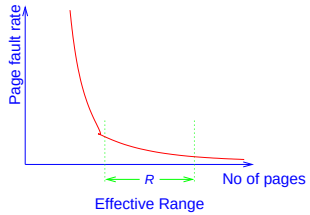
| 0 | 1 | 2 | 3 | 4 | 0 | 1 | 2 | 3 |
|---|---|---|---|---|---|---|---|---|
| x | x | x | 0 | 1 | 2 | 3 | 4 | 0 |
| x | x | 0 | 1 | 2 | 3 | 4 | 0 | 1 |
| x | 0 | 1 | 2 | 3 | 4 | 0 | 1 | 2 |
| 0 | 1 | 2 | 3 | 4 | 0 | 1 | 2 | 3 |

  (resident pages, oldest at top)
- here, five pages are needed continuously, but there are only four page frames
- under both LRU and FIFO policies, the page required next is removed!
  - this problem can only be solved if future page demand can be predicted!
  - problems are inevitable when the demand for pages exceeds the number of page frames available



## Paging Behaviour

- how many pages? (or, how big are the pages?)
  - too few (too big) can result in un-needed data put in main memory, resulting in page faults (when in 'steady-state')
  - too many results in huge page tables (and other large per-page overheads, including a large number of page faults initially, with a large number of disk accesses)

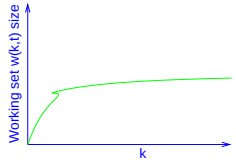



when program is in steady-state:

Assumption: page demand $<$ available pages in main memory

## Working Set

- the working set function $w(k,t)$ is defined as the set of pages accessed during the $k$ most recent memory accesses, up until time $t$




- as $k$ increases, the size of the $w(k,t)$ approaches a (constant) limit
  - this limit is the working set size at time $t$
  - it is roughly independent of $t$
- the working set size concept can be used to describe the memory needs of a program
  - if the main memory is not large enough to hold the working set, there will be excessive page faults (such behaviour is called thrashing)

  is also an imporntant concept in the memory hierarchy



## The Page Table in PeANUt

- is permanently located in page 0 (addresses **a0** to **a37**)
- it has 32 entries, each relating to one of the 32 VM pages
- 5 bits of a memory (VM) address are used to determine the page frame number, 5 bits for the offset within the page
- format of a page table entry:

| Unused | Last used | Swap count | D | P | Frame number |
|---|---|---|---|---|---|
| 15 11 | 10 8 | 7 5 | 4 | 3 | 2 0 |

- page table fields:
  - Last used: reflects how recently the page has been accessed (a value of 0 indicates that this is the most recently accessed page)
  - Swap count: indicates how many page faults have occurred since this page was loaded into memory (indicating its age)
  - Dirty flag: a value of 1 indicates that data has been written to this page since it was swapped into memory
  - Present flag: a value of 1 indicates the page is present in main memory
  - Frame number: states which page frame (slot in main memory) a page is in (*if* the page is present)



## PeANUt Virtual Memory Traps

- **`trap #11`**: page fault

  Is not user-initiated or user-definable. Can occur in the fetch of an instruction or the evaluation of its operand
- **`trap #12`**: swap page in

  Move page number AC from secondary memory to main memory. The O/S will use page table entry AC (at Mem[AC]) to determine the destination page frame
- **`trap #13`**: swap page out

  The O/S will move page number AC from main memory to secondary memory
- the handler routine for **`trap #11`** will use **`trap #12`** and **`trap #13`**, in accordance to which paging policy it uses
- example using the KeyTermFIFO policy: vmfifo.ass