ELF1 7D Virtual Memory

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2020-12-30 Wed

Outline

1. Based on

2. Virtual memory
   - Virtual memory
   - Kernal virtual / logical addresses
   - Kernel logical address
   - Kernel virtual address
   - User virtual address
   - Memory management unit
   - User space

Based on

"Study of ELF loading and relocs", 1999
http://netwinder.osuosl.org/users/p/patb/public_html/elf_relocs.html

Compling 32-bit program on 64-bit gcc

- `gcc -v`
- `gcc -m32 t.c`
- `sudo apt-get install gcc-multilib`
- `sudo apt-get install g++-multilib`
- `gcc-multilib`
- `g++-multilib`
- `gcc -m32`
- `objdump -m i386`

Virtual address and physical address (1)

- Physical addresses are provided directly by the machine
  - one physical address space per machine
  - addresses typically range
    from some minumum (sometimes0) to some maximum,
  - though some portions of this range are usually used
    by the OS and/or devices,
    but not available for user processes

https://www.student.cs.uwaterloo.ca/~cs350/F07/notes/mem.pdf

Virtual address and physical address (2)

- Virtual addresses (or logical addresses) are addresses provided by the OS
  - one virtual address space per process
  - addresses typically start at zero, but not necessarily
  - space may consist of several segments

https://www.student.cs.uwaterloo.ca/~cs350/F07/notes/mem.pdf

Virtual address and physical address (3)

- address translation (or address binding) means mapping virtual addresses to physical addresses

https://www.student.cs.uwaterloo.ca/~cs350/F07/notes/mem.pdf

Virtual address and physical address (4)

- size of each section except stack is specified in ELF file
- sections which are initialized from the ELF file
  - code (i.e., `.text`)
  - read-only data
  - initialized data segments
- other remaining sections are initially zero-filled
- sections have their own specified alignment
- segments are page aligned
- 3 segments = (`.text` + `.rodata`), (`.data` + `.sbss` + `.bss`), (stack)
- not all programs contain this many segments and sections

https://www.student.cs.uwaterloo.ca/~cs350/F07/notes/mem.pdf

Single address space (1)

- simple systems
- sharing the same memory space
  - memory and peripherals
  - all processes and OS
- no memory proctection

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Single address space (2)

- CPUs with single address space
  - 8086 - 80286
  - ARM Cortex-M
  - 8 / 16-bit PIC
  - AVR
  - most 8- and 16-bit systems

https://elinux.org/images/b/b0/Introduction_to_Memory_Management_in_Linux.pdf

Single address space (3)

- portable c programs expect flat memory
  - multiple memory access methods limit portability
- management is tricky
  - need to know / detect total RAM
  - need to keep processes separated
- no protection

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Virtual memory (1)

- a system that uses an address mapping
- maps virtual address space to physical address space
  - to physical RAM
  - to hardware devices
    - PCI devices
    - GPU RAM
    - On-SOC IP blocks

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Virtual memory (2)

- Advantages
  - each process can have a different memory mapping
    one process' RAM is invisible to other processes
    built in memory protection
    kernel RAM is invisiable to user space processes
  - memory can be moved
  - memory can be swapped to disk

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Virtual memory (3)

- Advantages (continued)
  - hardware device memory can be mapped
    into process' address space
    requires the kernel to perform the mapping
  - physical RAM can be mapped
    into multiple processes at once
    shared memory
  - memory regions can have access permissions
    read / write / execute

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Virtual memory (4)

- Physical addresses
  addresses used by the hardware (DMA, peripherals)
- Virtual addresses
  addresses used by software
  - RISC: load/store instructions
  - CISC: any instruction accessing memory

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Virtual memory (5)

- mapping is performed in hardware
- no performance penalty
  for accessing already mapped RAM regions
- permissions are handled without penalty
- the same instructions are used
  to access RAM and mapped hardware
- software will only use virtual addreses
  in its normal operation

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MMU (Memory Management Unit) (1)

- MMU is the hardware responsible for implementing virtual memory
- sits between the CPU core and memory
- usually the part of the physical CPU
  on ARM, it's part of the licensed core
- separate from the RAM controller
  DDR controller is a separate IP block

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MMU (Memory Management Unit) (2)

- transparently handels all memory accesses from load / store instructions
- maps memory acceses using virtual addresses to system RAM and peripheral hardware
- handles permissions
- generates an exception (page fault) on an invalid access

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TLB (Translation Lookaside Buffer)

- TLB is consulted by the MMU
  when CPU accesses a virtual address
- if the virtual address is in the TLB,
  the MMU can look up the physical address
- if the virtual address is not in the TLB,
  the MMU will generate a page fault exception
  and interrupt the CPU
- if the virtual address is in the TLB,
  but the permissions are insufficient,
  the MMU will generate a page fault

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Page faults

- a page fault is a CPU exception
  generated when software attempts
  to use an invalide virtual address
  - the virtual address is not mapped for the process requesting it
  - the processes has insufficient permissions for the address
  - the virtual address is valide, but swapped out

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Kernel virtual address (1)

- in linux, the kernel uses virtual addresses as user space processes do this is not true of all OS's
- virtual address space is split
    1. the upper part is used for the kernel
    2. the lower part is used for user space
    3. 32-bit linux have the split address 0xc0000000

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Kernel virtual address (2)

- By default, the kernel uses the top 1GB of virtual address space
- each user space process gets the lower 3GB of virtual address space

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Virtual addresses - linux (1)

- kernel address space is the area above CONFIG_PAGE_OFFSET
- for 32-bit, this is configurable at kernel build time
  - the kernel can be given a different amount of address space as desired
- for 64-bit, the split varies by architecture but it is high enough

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Virtual addresses - linux (2)

- three kinds of virtual addresses in Linux
- Kernel
  - Kernel Logical Address
  - Kernel Virtual Address
- User Space
  - User Virtual Address

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Kernel virtual / logical addresses (1)

- the kernel maps most of the *kernel virtual address space* to perform 1:1 mapping with an offset of the top part of physical memory (3GB - 4GB)
  - slightly *less then* for 1Gb for 32bit x86
  - can be different for other processors or configurations
- for kernel code on x86 address 0xc00000001 is mapped to physical address 0x1.
- This is called logical mapping
  - a 1:1 mapping (with an offset) that allows the kernel to access most of the physical memory of the machine.

https://stackoverflow.com/questions/8708463/difference-between-kernel-virtual-addr

Kernel virtual / logical addressess (2)

- in the following cases, the kernel keeps a region at the top of its virtual address space where it maps a "random" page
  - when we have *more then* 1Gb physical memory on a 32bit machine,
  - when we want to reference non-contiguous physical memory blocks as contiguous
  - when we want to map memory mapped IO regions
- this mapping does not follow the 1:1 pattern of the logical mapping area.
- This is called the virtual mapping.

https://stackoverflow.com/questions/8708463/difference-between-kernel-virtual-addr

Kernel virtual / logical addresses (3)

- on many platforms (x86 is an example), both the logical and virtual mapping are done using the same hardware mechanism (TLB controlling virtual memory).
- In many cases, the logical mapping is actually done using virtual memory facility of the processor, (this can be a little confusing)
- The difference is in which mapping scheme is used:
  - 1:1 for logical
  - random for virtual (paging)

https://stackoverflow.com/questions/8708463/difference-between-kernel-virtual-addr

Kernel virtual / logical addresses (4)

- 3 kinds of addressing

1. Logical Addressing : Address is formed by base and offset
   This is nothing but segmented addressing,
   where the address (or offset) in the program is always used
   with the base value in the segment descriptor

1. Linear Addressing : also called virtual address
   Here virtual adresses are contigous,
   but the physical address are not contiguous
   Paging is used to implement this.

1. Physical Addressing : the actual address on the Main Memory

https://stackoverflow.com/questions/8708463/difference-between-kernel-virtual-addr

Kernel virtual / logical addresses (5)

- in linux, the kernel memory (in address space) is beyond 3 GB, i.e. 0xc000000.
- the addresses used by Kernel are not physical addresses
  - to map the virtual address from 3GB to 4GB it uses `PAGE_OFFSET`.
    - no page translation is involved.
    - contiguous address
    - except 896 MB on x86.
  - beyond the address space from 3GB to 4GB, paging is used for translation.
    - `vmalloc` returns these addresses

https://stackoverflow.com/questions/8708463/difference-between-kernel-virtual-addr

Kernel virtual / logical addresses (6)

- when virtual memory is referred
  in context of user space,
  then it is through paging

- if kernel memory is mentioned
  then it is the address mapped
  - by `PAGE_OFFSET` (kernel logical address)
  - by `vmalloc` (kernel vitual address)

https://stackoverflow.com/questions/8708463/difference-between-kernel-virtual-addr

Kernel virtual / logical addresses (7)

- PAGE_OFFSET in x86 is 0XC0000000,
  (1100_0000_0000_0000_0000_0000_0000_0000)
  or 3 gigabytes ($3 * 2^{30}$)

- this is where the 3G/1G split is defined.

- every address above PAGE_OFFSET
  is the kernel virtual address

- any address below PAGE_OFFSET
  is a user space address

https://linux-mm.org/VirtualMemory

Kernel virtual / logical addresses (7)

- The kmalloc() & vmalloc() functions are a simple interface for obtaining kernel memory in byte-sized chunks.
- The kmalloc() function guarantees that the pages are physically contiguous (and virtually contiguous)
- The vmalloc() function allocates memory that is only virtually contiguous and not necessarily physically contiguous

https://stackoverflow.com/questions/116343/what-is-the-difference-between-vmalloc-

Kernel virtual / logical addresses (8)

- On a 32-bit system, kmalloc() returns the kernel logical address (its a virtual address though) which has the direct mapping (actually with constant offset) to physical address. This direct mapping ensures that we get a contiguous physical chunk of RAM. Suited for DMA where we give only the initial pointer and expect a contiguous physical mapping thereafter for our operation.
- vmalloc() returns the kernel virtual address which in turn might not be having a contiguous mapping on physical RAM. Useful for large memory allocation and in cases where we don't care about that the memory allocated to our process is continuous also in Physical RAM.

https://stackoverflow.com/questions/116343/what-is-the-difference-between-vmalloc-

Kernel virtual / logical addresses (9)

- Kernel logical addresses are mappings accessible to kernel code through normal CPU memory access functions. On 32-bit systems, only 4GB of kernel logical address space exists, even if more physical memory than that is in use. Logical address space backed by physical memory can be allocated with kmalloc.
- Virtual addresses do not necessarily have corresponding logical addresses. You can allocate physical memory with vmalloc and get back a virtual address that has no corresponding logical address (on 32-bit systems with PAE, for example). You can then use kmap to assign a logical address to that virtual address.

https://stackoverflow.com/questions/8708463/difference-between-kernel-virtual-addr

Kernel logical addresses (1)

- normal address space of the kernel
  `kmalloc()`
- virtual addresses are a fixed offset
  from their physical addresses
  virtual `0xc0000000` → physical `0x00000000`
- easy conversion between physical and virtual addresses

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Kernel logical addresses (2)

- kernel logical addreses can be converted to and from physical addresses using these macros
  `__pa(x)`
  `__va(x)`
- for small memory systems (less than 1G of RAM) kernel logical address space starts at `PAGE_OFFSET` and goes through the end of physical memory

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Kernel logical addresses (3)

- kernel logical address space includes
  - memory allocated with `kmalloc()` and most other allocation methods
  - kernel stacks per process
- kernel logical memory can never be swapped out

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Kernel logical addresses (4)

- kernel logical addresses use a fixed mapping between physical and virtual address space
- this means virtually contiguous regions are by nature also physically contiguous
- this combined with inability to be swapped out, makes them suitable for DMA transfers

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Kernel logical addresses (5)

- for 32-bit large memory systems (> 1GB RAM)
  not all of the physical RAM can be mapped
  into the kernel's address space
- kernel address space is the top 1GB of
  virtual address space, by default
- upto 104 MB is reserved at the top of
  the kernel memory space
  for non-contiguous allocation
  `vmalloc()`

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Kernel logical addresses (6)

- in a large memory case,
  only the bottom part of physical RAM
  is mapped directly into
  kernel logical address space
- only the bottom part of physical RAM has
  a kernel logical address
- this case is never applied to 64-bit systems
  - there is always enough kernel address space
    to accommodate all the RAM

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Low and High Memory

- low memory
  - physical memory which has a kernel logical address
  - physically contiguous
- high memory
  - physical memory beyond -~896MB
  - has no logical address
  - not physically contiguous when used in the kernel
  - only on 32-bit

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Kernel virtual addresses (1)

- kernel virtual addresses are
  above the kernel logical address mapping
- kernel virtual addresses - `vmalloc()`
- kernel logical addresses - `kmalloc()`

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Kernel virtual addresses (2)

- kernel virtual addresses are used for
  - non-contiguous memory mappings
    - often for large buffers which could potentially be too large to find contiguous memory
    - `vmalloc()`
  - memory-mapped I/O
    - map peripheral devices into kernel
    - PCI, SoC IP blocks
    - `ioremap()`, `kmap()`

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Kernel virtual addresses (3)

- the important difference is that memory in the kernel virtual address area (`vmalloc()` area) is non-contiguous physically
- this makes it easier to allocate, especially for large buffers on small memory systems
- this makes it unsuitable for DMA

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Kernel virtual addresses (4)

- in a large memory situation,
  the kernel virtual address area is smaller,
  because there is more physical memory
- an interesting case, where more memory means
  less space for kernel virtual addresses
- in 64-bit, of course, this doesn't happen,
  as PAGE_OFFSET is large, and
  there is much more virtual address space

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User virtual addresses (1)

- represent memory used by user space programs
  - the most of the memory on most systems
  - where the most of the compilation is
- all addresses below `PAGE_OFFSET`
- each process has its own mapping
  - threads share a mapping
  - complex behavior with `clone(2)`

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User virtual addresses (2)

- kernel logical addresses use a fixed mapping
  user space processes make full use of the MMU
  - only the used portions of RAM are mapped
  - memory is not contiguous
  - memory may be swapped out
  - memory can be moved

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User virtual addresses (3)

- since user virtual addresses are not guaranteed
  to be swapped in, or even allocated at all,
- user buffers are not suitable for use
  by the kernel (or for DMA), by default
- each process has its own memory map
  `struct mm` pointers in `task_struct`
- at context switch time, the memory map is changed
  this is part of the overhead

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Memory management unit (1)

- the MMU manages virtual address mappings
  - maps virtual addresses to physical addresses
- the MMU operates on basic units of memory : pages
  - page size varies by architecture
  - some architectures have configurable page sizes

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Memory management unit (2)

- common page sizes
  - ARM - 4k
  - ARM64 - 4k or 64k
  - MIPS - widely configurable
  - x86 - 4k

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Memory management unit (3)

- a page is
  - a unit of memory size
  - aligned at the page size
  - abstract
- a page frame refers to
  - a physical memory block
    which is page sized and page aligned
  - physical
- the pfn (page frame number) is often
  used to refer to physical page frames
  in the kernel

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Memory management unit (4)

- the MMU operates on pages
- the MMU maps physical frames to virtual addresses
- a memory map for a process contains many mappings
- a mapping often covers multiple pages
- the TLB holds each mapping
  - virtual address
  - physical address
  - permissions

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Page faults

- when a process acceses a region of memorythat is not mapped, the MMU will generate a page fault exception
- the kernel handles page fault exceptions regularly as part of its memory management design
- TLB can contain only the part of the required maps for a process
- page faults at context switch time
- lazy allocation

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Basic TLB mappings (1)

- user virtual address space
  - mapped pages unmapped space
- physical address space
  - allocated frames
- TLB mapings
  - TLB entries (page, page frame)
  - virtually contiguous regions
    not physically contiguous

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Basic TLB mappings (2)

- mappings to virtually contiguous regions
  do not have to be physically contiguous
- easy memory allocation
- almost all user space code does not need
  physically contiguous memory

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Multiple processes

- each *process* has its own set of mappings
- the same virtual addresses in two different processes will likely be used to map different physical addresses
  - (page, page frame1) for process 1
  - (page, page frame2) for process 2

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Shared memory (1)

- shared memory is easily implemented with an MMU
- simply map the same physical frame
  into two different processes
- the virtual addresses need not be the same
  - for pointers to values inside a shared memory region
    the virtual addresses must be the same

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Shared memory (2)

- the shared memory region can be mapped to different virtual addresses in each process
- the `mmap()` system call allows the user space process to request a specific virtual address to map the shared memory region
  - if the kernel cannot grant a mapping at this address, `mmap()` returns with failure

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Lazy allocation (1)

- the kernel does not allocate pages immeidately that are requested by a process
- the kernel will wait until those pages are actually used
- lazy allocation to optimize a performance
  - if the requested pages may not be actually used, then the allocation will never happen

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Lazy allocation (2)

- when memory is requested for allocation,
  the kernel simply creates
  a record of the *request* in its page tables
  and then returns (quickly) to the process,
  without updating the TLB

- when that newly-allocated memory is actually accessed,
  the CPU will generate a page fault,
  because the CPU doesn't know about the mapping
  (no entry in the TLB)

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Lazy allocation (3)

- in the page fault handler,
  the kernel uses its page tables
  to determine that the mapping is valid
  (from the kernel's point of view)
  yet unmapped in the TLB
- the kernel will allocate a physical page frame
  and update the TLB with the new mapping
- the kernel returns from the exception handler and
  user space program can resume

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Lazy allocation (4)

- in a lazy allocation case, the user space program is never aware that the page fault happened
- the page fault can only be detected at the time that was lost to handle it
- for processses that are time-sensitive pages can be pre-faulted, or simply touched, at the start of execution
  - see also `mlock()` and `mlockall()`

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Page tables (1)

- the entries in the TLB are a limited resource
- far more mappings can be made than can exist in the TLB at one time
- the kernel must keep track of all of the mappings at all times
- the krenel stores all these informations in the page tables `stuct_mm` and `vm_area_struct`

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Page tables (2)

- since the TLB can only hold a limited subset of the total mappings for a process, some valid mappings will not have TLB entries
- when these addresses are touched the CPU will generate a page fault because the CPU has no knowledge of the mapping only the kernel does

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Page tables (3)

- the page fault handler will
  - find the appropriate mapping for the offending addresses in the krenel's page tables
  - select and remove an existing TLB entry
  - create a TLB entry for the page containing the address
  - return to the user space process
    - observe the similarities to lazy allocation handling

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Swapping (1)

- when memory utilization is high,
  the kernel may swap some frames to disk
  to free up RAM
- the MMU makes this possible
  - the kernel may copy a frame to disk and
    remove its TLB entry
  - the frame may be reused by another process

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Swapping (2)

- when the frame is needed again,
  the CPU will generate a page fault
  because the address is not in the TLB
- at a page fault time, the kernel can
  - put the process to sleep
  - copy the frame from the disk
    into an unused frame in RAM
  - fix the page table entry
  - wake the process

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Swapping (3)

- note that when the page is restored to RAM,
  it is not necessarily restored to the same physical frame
  where it originally was located (before being swapped out)

- the MMU will use the same virtual address though,
  so the user space program will not know the difference
  - this is why user space memory cannot
    typically be used for DMA

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User space

- there are several ways to allocate memory from user space
  - ignoring the familiar `*alloc()` functions, which sit on top of platform methods
- `mmap()` can be used directly to allocate and map pages
- `brk()` / `sbrk()` can be used to increase the heap size

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mmap()

- mmap() is the standard way to allocate large amounts of memory from user space
- while mmap() is often used for files, the MAP_ANONYMOUS flag causes mmap() to allocate normal memory for the process
- the MAP_SHARED flag can make the allocated pages sharable with other processes

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brk() / sbrk() (1)

- brk() sets the top of the program break
- this is the top of the data segment
  but inspecton of kernel/sys.c shows
  it separates from the data segment
- this in effect increases the size of the heap
- sbrk() increases the program break
  rather than setting it directly

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brk() / sbrk() (2)

- lazy allocation
- see mm/mmap.c for do_brk()
- do_brk() is implemented similar to ~mmap()
- modify the page tables for the new area
- wait for the page fault
- optionally, do_brk() can pre-fault the new area
  and allocate it
  see mlock(2) to control this behavior

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High level implementation

- malloc() and calloc() will use
  either brk() or mmap()
  depending on the requested allocation size
  - small allocations use brk()
  - large allocaion use mmap()
  - see mallopt(3) and the M_MMAP_THRESHOD parameter
    to control this behavio

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Stack

- Stack expansion
- if a process accesses memory beyond its stack,
  the CPU will trigger a page fault
- the page fault handler detects
  the address is just beyond the stack, and
  allocates a new page to extend the stack
- the new page will not be physically contiguous
  with the rest of the stack
- see `__do_page_fault()` in `/arch/arm/mm/fault.c`

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