

ELF1 7D Virtual Memory

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1 Based on

2 Virtual memory

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

"Study of ELF loading and relocs", 1999

http://netwinder.osuosl.org/users/p/patb/public_html/elf_relocs.html

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Compiling 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 minimum (sometimes 0) 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 protection

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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://elixir.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

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

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 invisible 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 addresses 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 handles all memory accesses from load / store instructions
- maps memory accesses 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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- 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 than for 1Gb for 32bit x86
 - can be different for other processors or configurations
- for kernel code on x86 address 0xc0000001 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-address>

Kernel virtual / logical addresses (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 than **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-add>

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-addresses>

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** addresses are contiguous,
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-address>

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-address>

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 virtual address)

<https://stackoverflow.com/questions/8708463/difference-between-kernel-virtual-address>

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 (8)

- to get kernel memory in byte-sized chunks.
 - `kmalloc()`
 - virtually contiguous
 - physically contiguous
 - `vmalloc()`
 - virtually contiguous
 - not necessarily physically contiguous

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

Kernel virtual / logical addresses (9)

- On a 32-bit system, `kmalloc()`
 - returns the kernel **logical** address (it is a virtual address)
 - the **direct** mapping (constant offset)
 - a contiguous **physical** chunk of RAM.
 - suitable for DMA where we give only
- `vmalloc()`
 - returns the kernel **virtual** address
 - **paging** (not direct mapping)
 - not necessarily a contiguous chunk of RAM
 - Useful for large memory allocation and in cases where non-contiguous physical memory is allowed

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

Kernel virtual / logical addresses (10)

- kernel **logical** addresses use 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 supported by **physical** memory can be allocated with `kmalloc()`

<https://stackoverflow.com/questions/8708463/difference-between-kernel-virtual-address>

Kernel virtual / logical addresses (11)

- kernel **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).
- use **kmap()** to assign a **logical** address to that **virtual** address.

<https://stackoverflow.com/questions/8708463/difference-between-kernel-virtual-address>

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 addresses 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 accesses a region of memory that 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 mappings
 - 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 immediately 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 processes 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 kernel 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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- the **page fault handler** will
 - find the appropriate mapping for the offending addresses in the kernel'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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- 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 inspection 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 allocation use `mmap()`
 - see `mallopt(3)` and the `M_MMAP_THRESHOLD` parameter to control this behavior

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- 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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