Lens: Experiencing Multi-level Page Tables at Close Quarters

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Importance of Operating Systems

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- OS is a building block in today's digital world.

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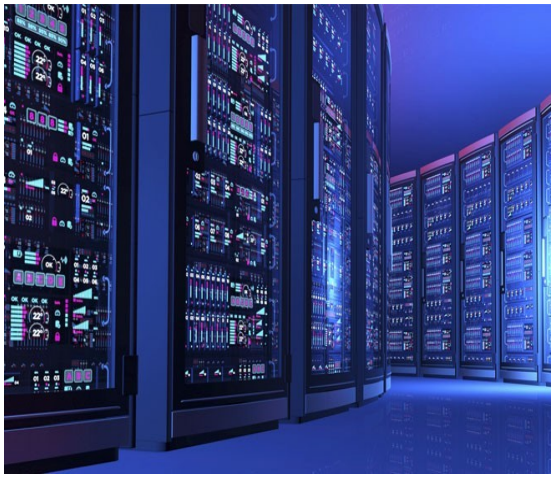

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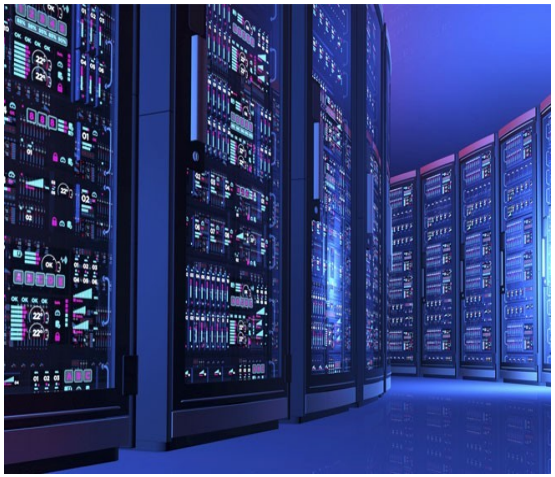

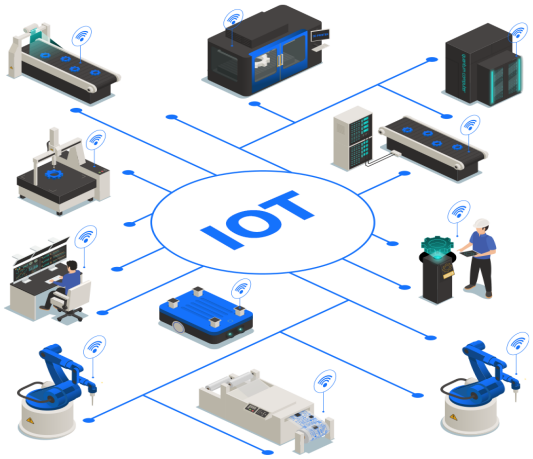

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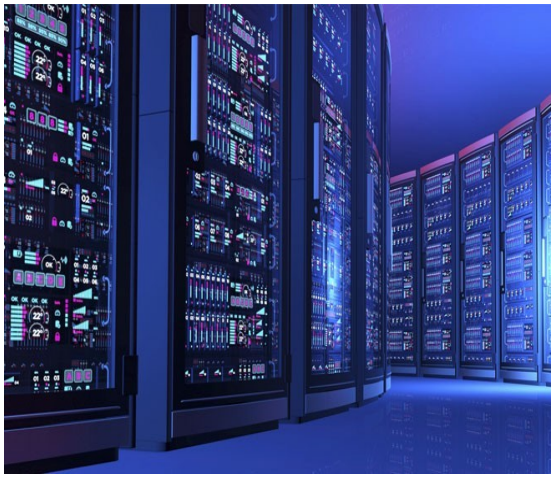

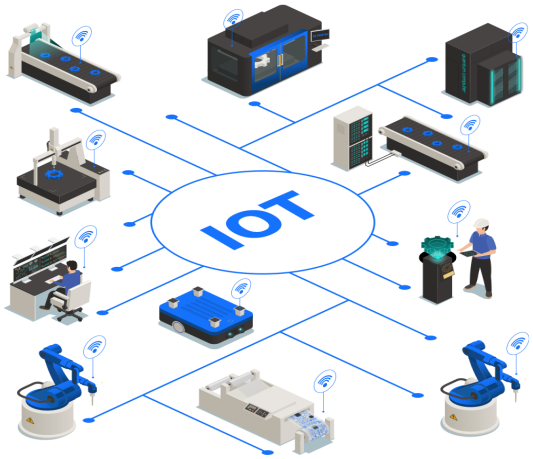

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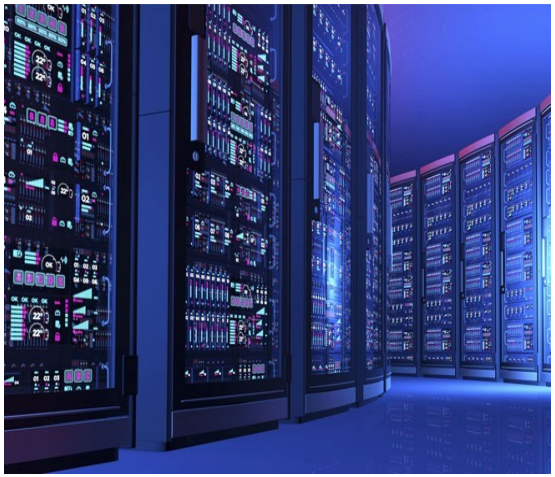

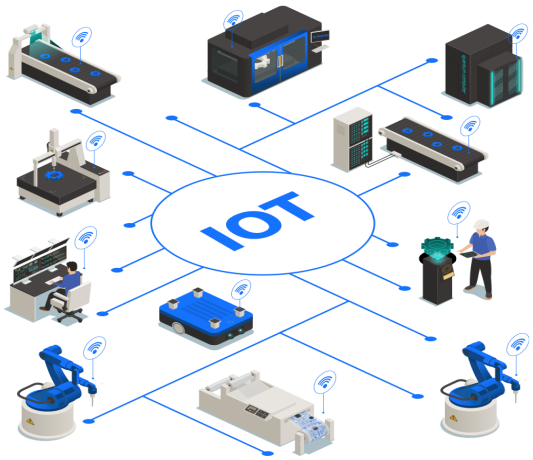

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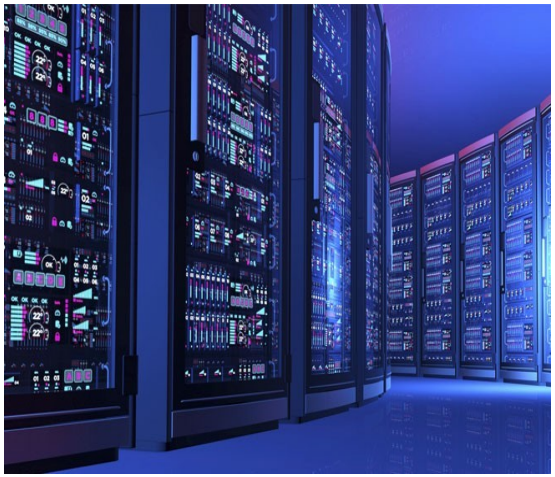

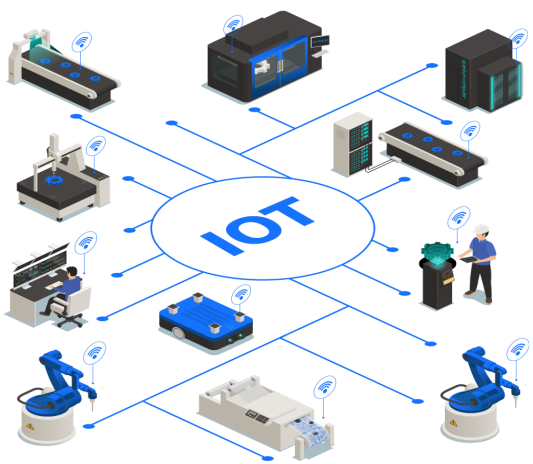

Importance of Operating Systems

- OS is a building block in today's digital world.
- OS helps us to perform our day-to-day digital activities better.




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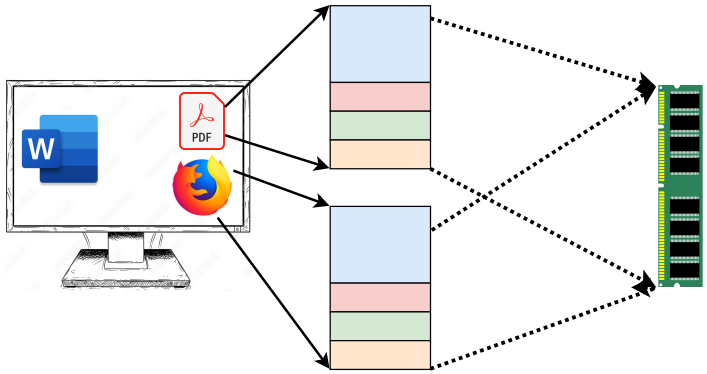
- OS helps us to perform our day-to-day digital activities better.
- OS encompasses multiple subsystems such as File system, Virtual Memory, and the interplay between them.




The Virtual Memory Sub-system

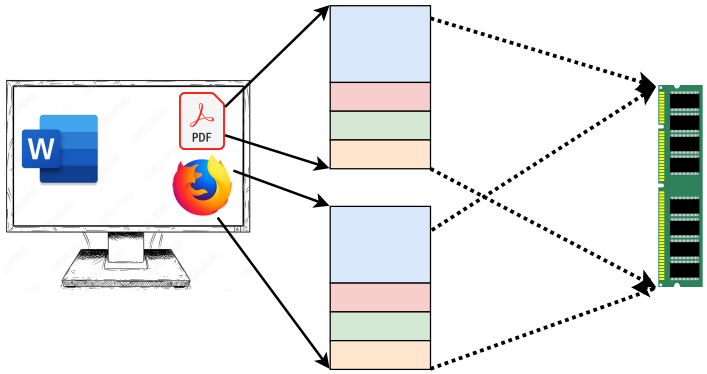
Understanding the VM Sub-system

- Virtual memory allows inter-process isolation.



Understanding the VM Sub-system

- Virtual memory allows inter-process isolation.
- Each process has an independent view of memory.



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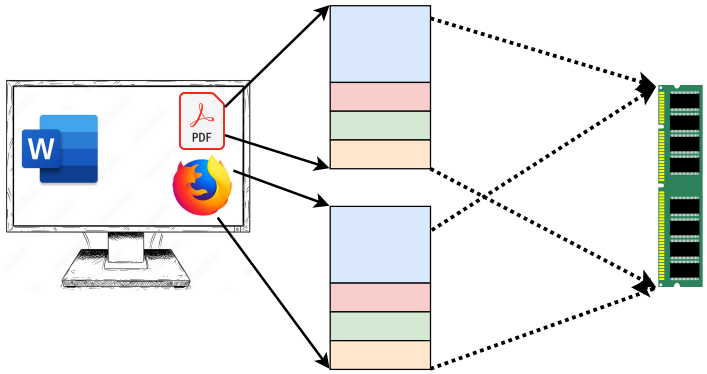
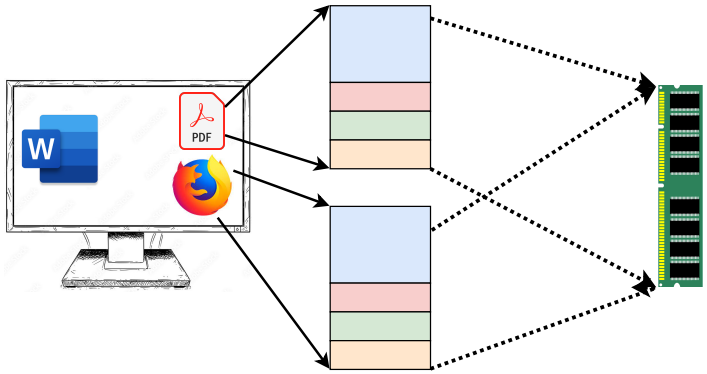


Understanding the VM Sub-system

- Virtual memory allows inter-process isolation.
- Each process has an independent view of memory.
- Virtual memory makes a programmer's life easy.
- Virtual memory facilitates memory access permission.



Understanding the VM Sub-system

Text Books

✓ Use simple examples to explain concepts

Educational OS

Debugging Interfaces

Understanding the VM Sub-system

Text Books

✓ Use simple examples to explain concepts

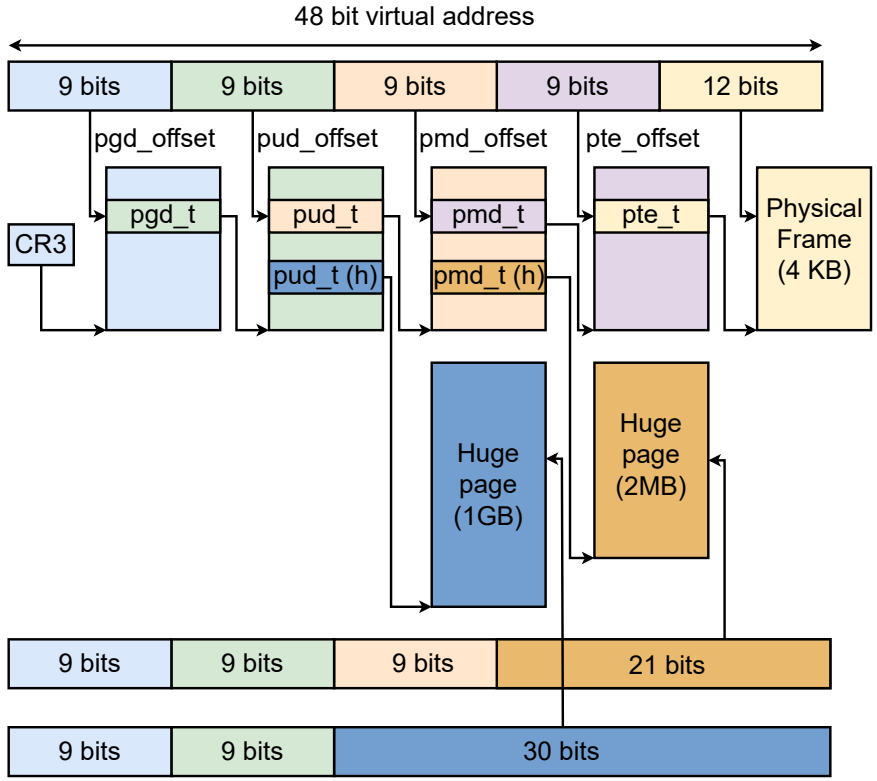
✗ Do not capture real-world complexities

Educational OS

Debugging Interfaces

Page table in Intel x86-64 processor

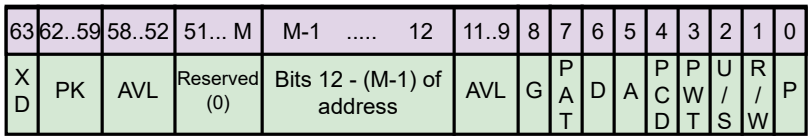
- 4 level paging translates 48 bit virtual address to physical address.
- Allows translation into 4 KB, 2MB, and 1 GB pages.
- Each entry provides details about the next level page.



Ref: [Guide(2011)]

Page table entry in Intel x86-64 system

- PTE captures access permissions, access mode and other details.
- Intel software manual details page table structures and different configurations.
- Challenging for a beginner to correlate page table details with a program's virtual memory state.



P: Present
R/W: Read/Write
U/S: User/Supervisor
PWT: Write-Through
PCD: Cache Disable
A: Accessed
D: Dirty
G: Global
AVL: Available
PAT: Page Attribute Table
M: Maximum Physical Address Bit
PK: Protection Key
XD: Execute Disable

Ref: [Guide(2011)]

Understanding the VM Sub-system

Text Books

Educational OS

- ✓ Profiling the code with debug statements

Debugging Interfaces

Understanding the VM Sub-system

Text Books

Educational OS

✓ Profiling the code with debug statements

✗ Requires understanding the code base

Debugging Interfaces

Understanding the VM Sub-system

Text Books

Educational OS

Debugging Interfaces

✓ Reading the interface for fetching predefined virtual memory details

Understanding the VM Sub-system

Text Books

Educational OS

Debugging Interfaces

✓ Reading the interface for fetching predefined virtual memory details

✗ Gives limited information for education

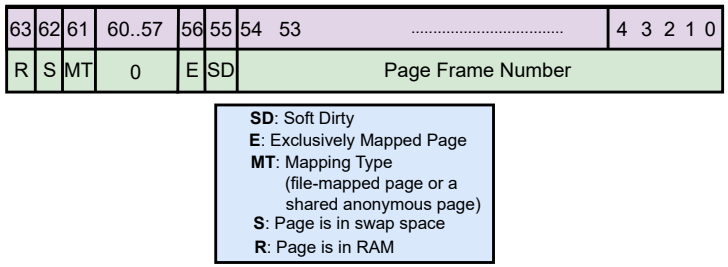
VM interfaces in Linux

- */proc/pid/maps* shows currently mapped memory regions.
- */proc/pid/maps* is a pseudo file maintained under proc file system for each process.
- It is not straightforward to correlate a program variable address with information from */proc/pid/maps*.

```
55a4c3600000-55a4c3601000 r-xp 00000000 08:02 25958718 program_code
55a4c3800000-55a4c3801000 r--p 00000000 08:02 25958718  program_code
55a4c3801000-55a4c3802000 rw-p 00001000 08:02 25958718  program_code
55a4c55fa000-55a4c561b000 rw-p 00000000 00:00 0         [heap]
7f4407200000-7f44073e7000 r-xp 00000000 08:02 36177205  libc-2.27.so
7f44073e7000-7f44075e7000 ---p 001e7000 08:02 36177205  libc-2.27.so
7f44075e7000-7f44075eb000 r--p 001e7000 08:02 36177205  libc-2.27.so
7f44075eb000-7f44075ed000 rw-p 001eb000 08:02 36177205  libc-2.27.so
7f44075ed000-7f44075f1000 rw-p 00000000 00:00 0
7f4407600000-7f4407629000 r-xp 00000000 08:02 36177201  ld-2.27.so
7f4407829000-7f440782a000 r--p 00029000 08:02 36177201  ld-2.27.so
7f440782a000-7f440782b000 rw-p 0002a000 08:02 36177201  ld-2.27.so
7f440782b000-7f440782c000 rw-p 00000000 00:00 0
7f4407929000-7f440792b000 rw-p 00000000 00:00 0
7ffd9028a000-7ffd902ab000 rw-p 00000000 00:00 0         [stack]
7ffd9034b000-7ffd9034f000 r--p 00000000 00:00 0         [vvar]
7ffd9034f000-7ffd90351000 r-xp 00000000 00:00 0         [vdso]
ffffffffff600000-ffffffffff601000 --xp 00000000 00:00 0 [vsyscall]
```

VM interfaces in Linux

- */proc/pid/pagemap* shows virtual to physical page mapping.
- It requires calculating the file offset corresponding to a program variable in the pagemap file to get its physical page.
- Only gives information in the last level of a page table (PTE).



Tool for Learning Virtual Memory

Features of an educational tool for VM

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- Presents an interface that is easy-to-use.
- Expects only basic C programming knowledge from learners.
- Allows learners to correlate program execution with memory state.
- Visualizes details for easy understanding by learners.
- Shows changes in real-time by updating visualization in sync with program changes.

Lens: An Education Tool for VM

What does Lens offer?

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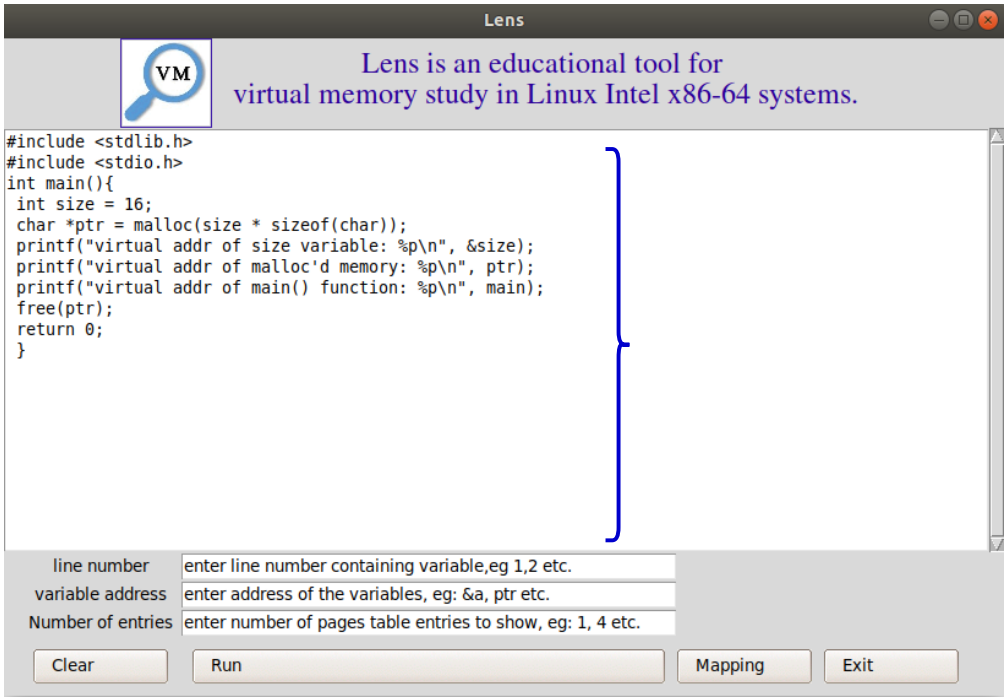

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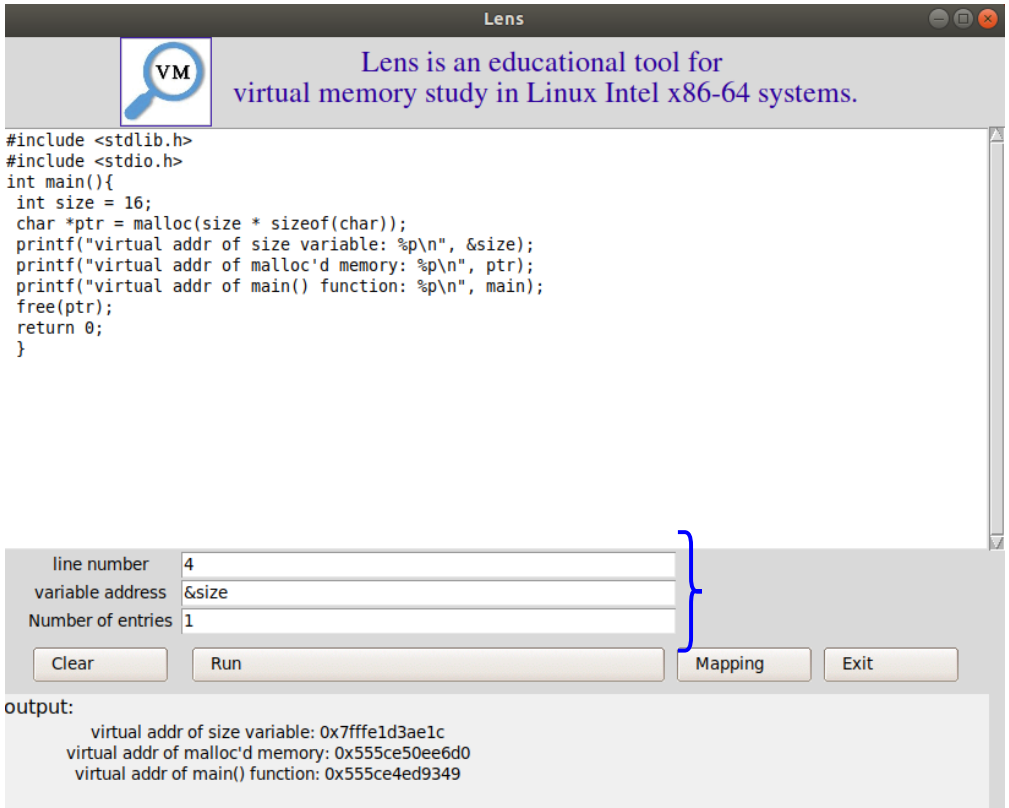
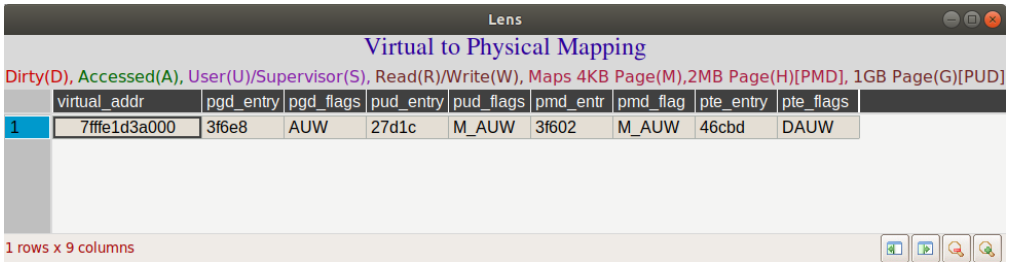


What does Lens offer?

- Provides a practical exposure to virtual memory in Linux.
- Provides an interface to
  - Write C programs.
  - Correlate program execution with memory state.
  - Visualize virtual to physical address translation.



Start Video

What does Lens offer?

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  - Write C programs.
  - Correlate program execution with memory state.
  - Visualize virtual to physical address translation.
- Covers underlying hardware-OS complexities.

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- Provides a practical exposure to virtual memory in Linux.
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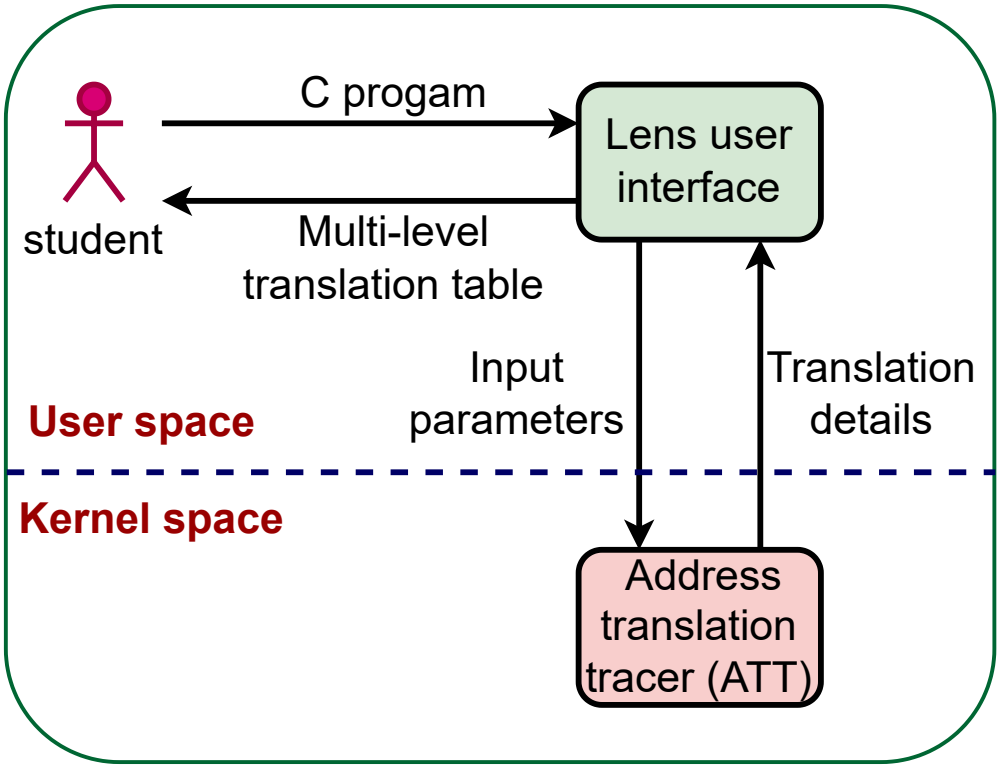
  - Write C programs.
  - Correlate program execution with memory state.
  - Visualize virtual to physical address translation.
- Covers underlying hardware-OS complexities.
- Shows address translation table with latest updates in program.

High level view of Lens

- Student interacts with graphical interface.
- ATT handles underlying hardware-OS complexities.



Example use cases with Lens

- Lazy page allocation in Linux.
- Linux allocates physical pages on first access.

Inspecting lazy page allocation

```
1 #define TWOMB 2097152
2 int main(int argc, char* argv[]){
3     char * ptr = (char*)mmap(NULL, TWOMB, PROT_READ|PROT_WRITE, MAP_PRIVATE|
      MAP_ANONYMOUS,0,0);
4     ptr[0] = 'A';
5     printf("ptr:%p\n",ptr);
6     ptr[4096] = 'B';
7     mprotect(&ptr[4096],4096,PROT_READ);
8     munmap(ptr, TWOMB);
9     return 0;}
```

Inspecting at line number 4

Inspecting lazy page allocation

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Inspecting at line number 4

pud_entry	pud_flags	pmd_entry	pmd_flags	pte_entry	pte_flags
36d4b	M_AUW	ffa2	M_AUW	1c8e4	DAUW
36d4b	M_AUW	ffa2	M_AUW	0	____

Example use cases with Lens

- Lazy page allocation in Linux.
- Linux allocates physical pages on first access.
- Changing memory access permission.
- Linux provides *mprotect* sys call to change access protection of pages.

Changing memory access permission

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Inspecting at line number 7

Changing memory access permission

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       MAP_ANONYMOUS,0,0);
4     ptr[0] = 'A';
5     printf("ptr:%p\n",ptr);
6     ptr[4096] = 'B';
7     mprotect(&ptr[4096],4096,PROT_READ);
8     munmap(ptr, TWOMB);
9     return 0;}
```

Inspecting at line number 7

pud_entry	pud_flags	pmd_entry	pmd_flags	pte_entry	pte_flags
36d4b	M_AUW	ffa2	M_AUW	1c8e5	DAUR

Example use cases with Lens

- Lazy page allocation in Linux.
- Linux allocates physical pages on first access.
- Changing memory access permission.
- Linux provides *mprotect* sys call to change access protection of pages.
- Lens can also provide insights to other virtual memory concepts like hugepages.

Future Directions

- Use Lens in an OS course for collecting feedback.
- Show address translation table as a radix tree and make the interface interactive for students to zoom-in.
- Visualize more virtual memory changes such addition, deletion and merging of VM areas, stack/heap growth and shrink with changes in program.
- Visualize more OS activities related to virtual memory, like page faults.

Conclusion

- Practical understanding of virtual to physical address translation is essential in learning virtual memory.
- Students require hands-on experience with virtual memory concepts to enhance their learning.
- Lens provides an easy interface for students to write C code and correlate program state with changes in virtual memory.
- Lens helps students in gaining practical exposure to virtual memory concepts.
- Lens is available at https://github.com/arunkp1986/Lens.git

Thank You!

Questions?

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References

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