Cloud Operating Systems

PIC and PIT

Andreas Kogler, Fabian Rauscher, Daniel Gruss

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Outlook

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- Classic hardware interactions

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- Why should *your* **HV** care?

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- What is the PIC?
- What is the PIT?
- Why should *your* **HV** care?
- How to virtualize the PIC and PIT

Hardware Interactions?

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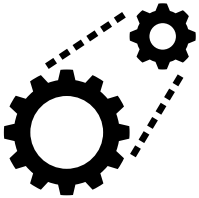

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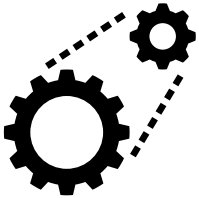

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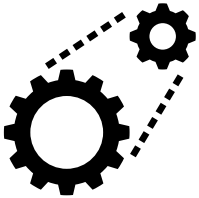

- draw a character on the console?

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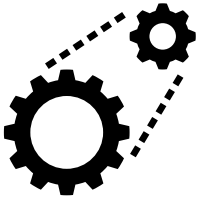

- draw a character on the console?
- receive a keyboard press?

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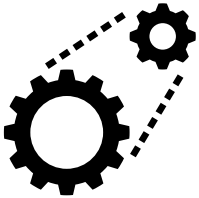
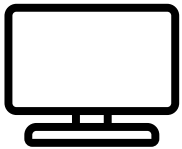


- draw a character on the console?
- receive a keyboard press?
- receive a regular *heartbeat*?

Console Output



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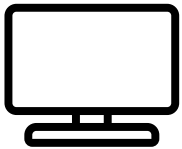

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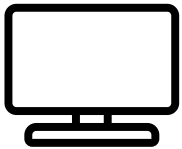

- **frame buffer** at physical address `0xB8000`

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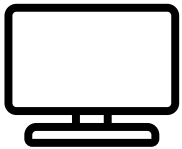

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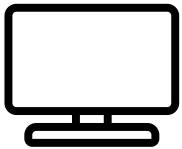

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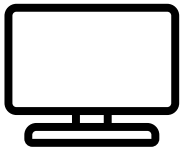
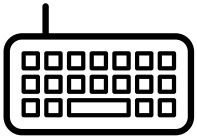


- **frame buffer** at physical address `0xB8000`
- how to pass the buffer to the guest?
  - share it via the EPT?
  - copy it, but when?

Keyboard



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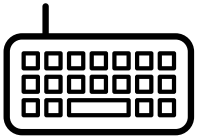

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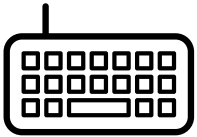

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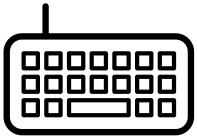

- implemented via interrupts and ports
- check if data is available on port `0x64`

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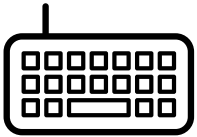

- implemented via interrupts and ports
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- get the current *scancode* key value from port `0x60`

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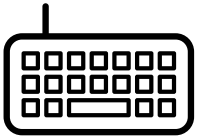

- implemented via interrupts and ports
- check if data is available on port `0x64`
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- but how to share with a guest?

- How and when to preempt threads?

Heartbeat

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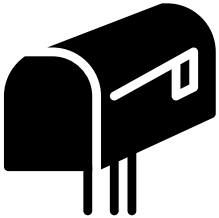
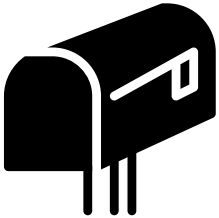
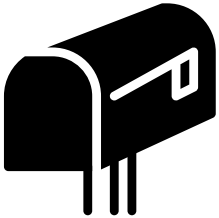
- But how to pass this heartbeat to the guest?

Programmable Interrupt Controller







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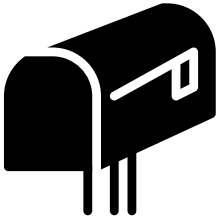

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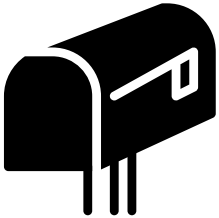

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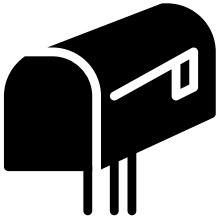

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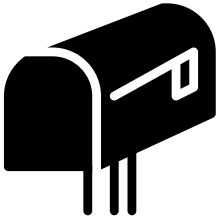

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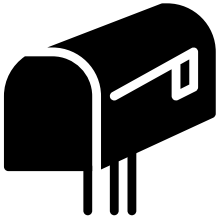

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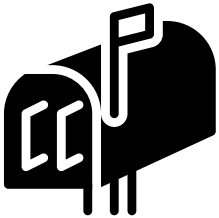

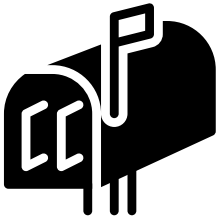

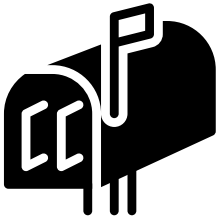

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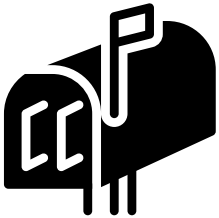

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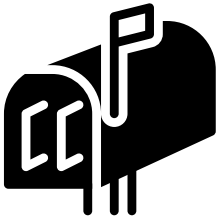

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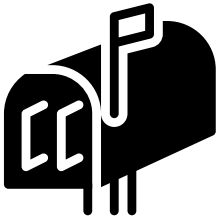

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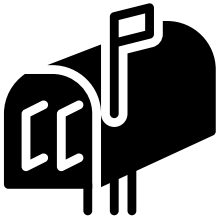

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- Most known command: End-Of-Interrupt (EOI) **D=0x20**

PIC Setup

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- Important hardware IRQs:
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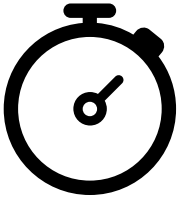
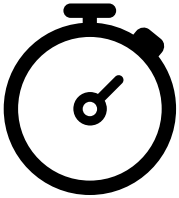
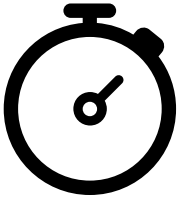
  - **0**: Timer interrupt
  - **1**: Keyboard interrupt

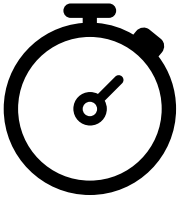
Programmable Interval Timer







- Basically a programmable oscillator, with selectable:



- Basically a programmable oscillator, with selectable:
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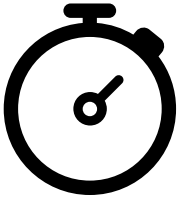

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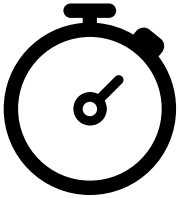

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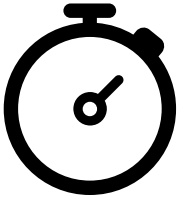

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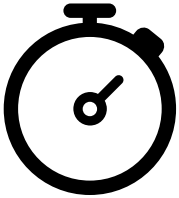

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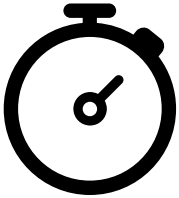

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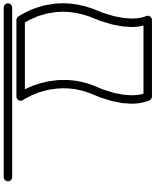

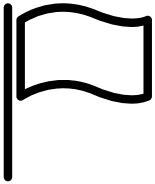

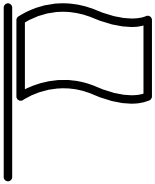

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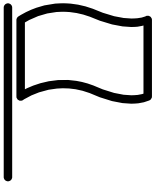

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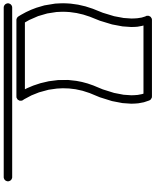

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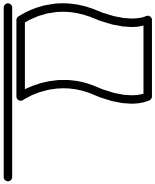
- Channel 0 counts with 18.2065 Hz
- Giving an **interrupt** every $\approx$ 54 ms



- Needed by the scheduler to change threads
- Channel 0 counts with 18.2065 Hz
- Giving an **interrupt** every $\approx$ 54 ms
- If enabled in the **PIC**

How to virtualize PIC and PIT?

1. Check pending interrupts
   → Keyboard, Keyboard

Int. Window Exiting	0
Int. Info.	0
rflags.IF	0
pending IRQs	Keyboard

Event Injection - Example

1. Check pending interrupts
   $\rightarrow$ Keyboard, Keyboard
2. Check guest IF flag $\rightarrow$ 0

Int. Window Exiting	0
Int. Info.	0
rflags.IF	0
pending IRQs	Keyboard

Event Injection - Example

1. Check pending interrupts
   → Keyboard, Keyboard
2. Check guest IF flag → 0
3. Set interrupt-window exiting

Int. Window Exiting	1
Int. Info.	0
rflags.IF	0
pending IRQs	Keyboard

Event Injection - Example

1. Check pending interrupts
   → Keyboard, Keyboard
2. Check guest IF flag → 0
3. Set interrupt-window exiting
4. Continue guest

Int. Window Exiting	1
Int. Info.	0
rflags.IF	0
pending IRQs	Keyboard

```
push    rbp
mov     rbp, rsp
sti
nop
pop     rbp
ret
```

Int. Window Exiting	1
Int. Info.	0
rflags.IF	0
pending IRQs	Keyboard

Event Injection - Example

```
push    rbp
mov     rbp, rsp
sti
nop
pop     rbp
ret
```

Int. Window Exiting	1
Int. Info.	0
rflags.IF	0
pending IRQs	Keyboard

Event Injection - Example

```
push    rbp
mov     rbp, rsp
sti
nop
pop     rbp
ret
```

Int. Window Exiting	1
Int. Info.	0
rflags.IF	0
pending IRQs	Keyboard

Event Injection - Example

```
push    rbp
mov     rbp, rsp
sti
nop
pop     rbp
ret
```

Int. Window Exiting	1
Int. Info.	0
rflags.IF	1
pending IRQs	Keyboard

```
push    rbp
mov     rbp, rsp
sti
nop
pop     rbp
ret
```

Int. Window Exiting	1
Int. Info.	0
rflags.IF	1
pending IRQs	Keyboard

Event Injection - Example

1. VM Exit → VMM takes control

Int. Window Exiting	1
Int. Info.	0
rflags.IF	1
pending IRQs	Keyboard

Event Injection - Example

1. VM Exit → VMM takes control
2. Check VM Exit reason
   → interrupt window

Int. Window Exiting	1
Int. Info.	0
rflags.IF	1
pending IRQs	Keyboard

Event Injection - Example

1. VM Exit → VMM takes control
2. Check VM Exit reason
   → interrupt window
   2.1 Check pending interrupts
   → Keyboard, Keyboard

Int. Window Exiting	1
Int. Info.	0
rflags.IF	1
pending IRQs	Keyboard

Event Injection - Example

1. VM Exit → VMM takes control
2. Check VM Exit reason
   → interrupt window
   2.1 Check pending interrupts
   → Keyboard, Keyboard
   2.2 Set interruption information

Int. Window Exiting	0
Int. Info.	0x80000021
rflags.IF	1
pending IRQs	Keyboard

Event Injection - Example

1. VM Exit → VMM takes control
2. Check VM Exit reason
   → interrupt window
   - 2.1 Check pending interrupts
     → Keyboard, Keyboard
   - 2.2 Set interruption information
   - 2.3 Continue guest

Int. Window Exiting	0
Int. Info.	0x80000021
rflags.IF	1
pending IRQs	

Event Injection - Example

```
push    rbp
mov     rbp, rsp
sti
nop
pop     rbp
ret
```

Int. Window Exiting	0
Int. Info.	0x80000021
rflags.IF	1
pending IRQs	

```
push    rbp
mov     rbp, rsp
sti
nop
pop     rbp
ret
```

Int. Window Exiting	0
Int. Info.	0x80000021
rflags.IF	1
pending IRQs	

```
<irq handler>
in EAX, 0x64
iret
```

Int. Window Exiting	0
Int. Info.	0x80000021
rflags.IF	0
pending IRQs	

Event Injection - Example

```
<irq handler>
in EAX, 0x64
iret
```

Int. Window Exiting	0
Int. Info.	0x80000021
rflags.IF	0
pending IRQs	

Event Injection - Example

1. IN and OUT always use EAX, AL, AX

Int. Window Exiting	0
Int. Info.	0x80000021
rflags.IF	0
pending IRQs	

Event Injection - Example

1. IN and OUT always use EAX, AL, AX
2. Hypervisor injects value
3. Hypervisor advances RIP

Int. Window Exiting	0
Int. Info.	0x80000021
rflags.IF	0
pending IRQs	

Event Injection - Example

1. IN and OUT always use EAX, AL, AX
2. Hypervisor injects value
3. Hypervisor advances RIP
4. Continue Guest

Int. Window Exiting	0
Int. Info.	0x80000021
rflags.IF	0
pending IRQs	

Event Injection - Example

1. IN and OUT always use EAX, AL, AX
2. Hypervisor injects value
3. Hypervisor advances RIP
4. Continue Guest

Int. Window Exiting	0
Int. Info.	0x80000021
rflags.IF	0
pending IRQs	

Virtualized PIC and PIT

Virtualized PIC and PIT

- Examine VMExits based on IO port operations

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- Emulate PIC and PIT for their ports

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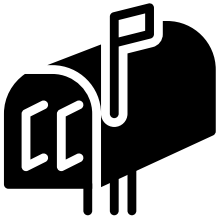
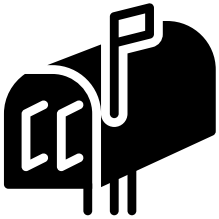
Virtualized PIC and PIT

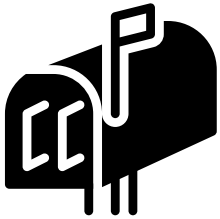
- Examine VMExits based on IO port operations
- Emulate PIC and PIT for their ports
- You don't need to implement all features
  - only what SWEB needs
  - check SWEB's code if unsure

Virtualized PIC

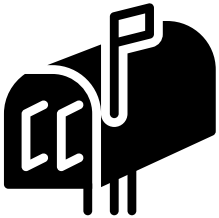


Virtualized PIC

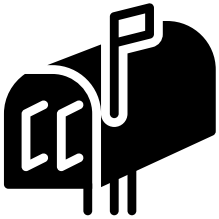




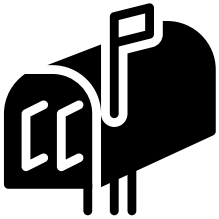
- Emulate the ports for the configuration:



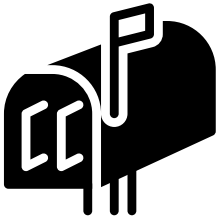
- Emulate the ports for the configuration:
  - the offset mapping HW IRQ to interrupt vectors



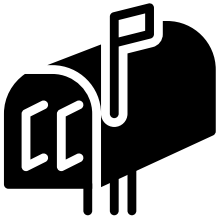
- Emulate the ports for the configuration:
  - the offset mapping HW IRQ to interrupt vectors
  - the interrupt mask enabling and disabling interrupts



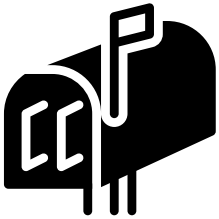
- Emulate the ports for the configuration:
  - the offset mapping HW IRQ to interrupt vectors
  - the interrupt mask enabling and disabling interrupts
  - ...



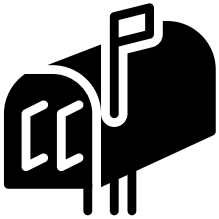
- Emulate the ports for the configuration:
  - the offset mapping HW IRQ to interrupt vectors
  - the interrupt mask enabling and disabling interrupts
  - ...
- Forward only enabled interrupts to the guest



- Emulate the ports for the configuration:
  - the offset mapping HW IRQ to interrupt vectors
  - the interrupt mask enabling and disabling interrupts
  - ...
- Forward only enabled interrupts to the guest
- Manage pending interrupts in the HV

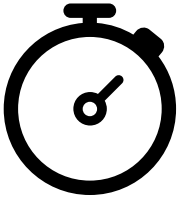


- Emulate the ports for the configuration:
  - the offset mapping HW IRQ to interrupt vectors
  - the interrupt mask enabling and disabling interrupts
  - ...
- Forward only enabled interrupts to the guest
- Manage pending interrupts in the HV
- Think about interrupts during interrupts (hint: EOI)

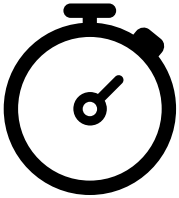


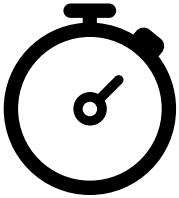
- Emulate the ports for the configuration:
  - the offset mapping HW IRQ to interrupt vectors
  - the interrupt mask enabling and disabling interrupts
  - ...
- Forward only enabled interrupts to the guest
- Manage pending interrupts in the HV
- Think about interrupts during interrupts (hint: EOI)
- Goal: Be able to forward keyboard scancodes to the guest

Virtualized PIT

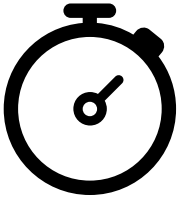


Virtualized PIT

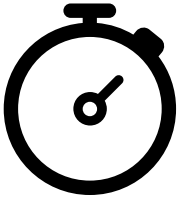




- Emulate the ports similar to the PIC



- Emulate the ports similar to the PIC
- Generate timer interrupts if enabled in the PIC



- Emulate the ports similar to the PIC
- Generate timer interrupts if enabled in the PIC
- Goal: Generate timer interrupts for the guest's scheduler

- Register: CPU_BASED_VM_EXEC_CONTROL

- Register: CPU_BASED_VM_EXEC_CONTROL
  - Bit: CPU_BASED_VIRTUAL_INTR_PENDING

- Register: CPU_BASED_VM_EXEC_CONTROL
  - Bit: CPU_BASED_VIRTUAL_INTR_PENDING
- Register: VM_ENTRY_INTR_INFO_FIELD

- Register: CPU_BASED_VM_EXEC_CONTROL
  - Bit: CPU_BASED_VIRTUAL_INTR_PENDING
- Register: VM_ENTRY_INTR_INFO_FIELD
- Register: VMX_PREEMPTION_TIMER_VALUE

- Register: CPU_BASED_VM_EXEC_CONTROL
  - Bit: CPU_BASED_VIRTUAL_INTR_PENDING
- Register: VM_ENTRY_INTR_INFO_FIELD
- Register: VMX_PREEMPTION_TIMER_VALUE
- ExitReasons: INT_WINDOW, IO_INST and NMI

Questions?