CLOUDBURST

A VMware Guest to Host Escape Story

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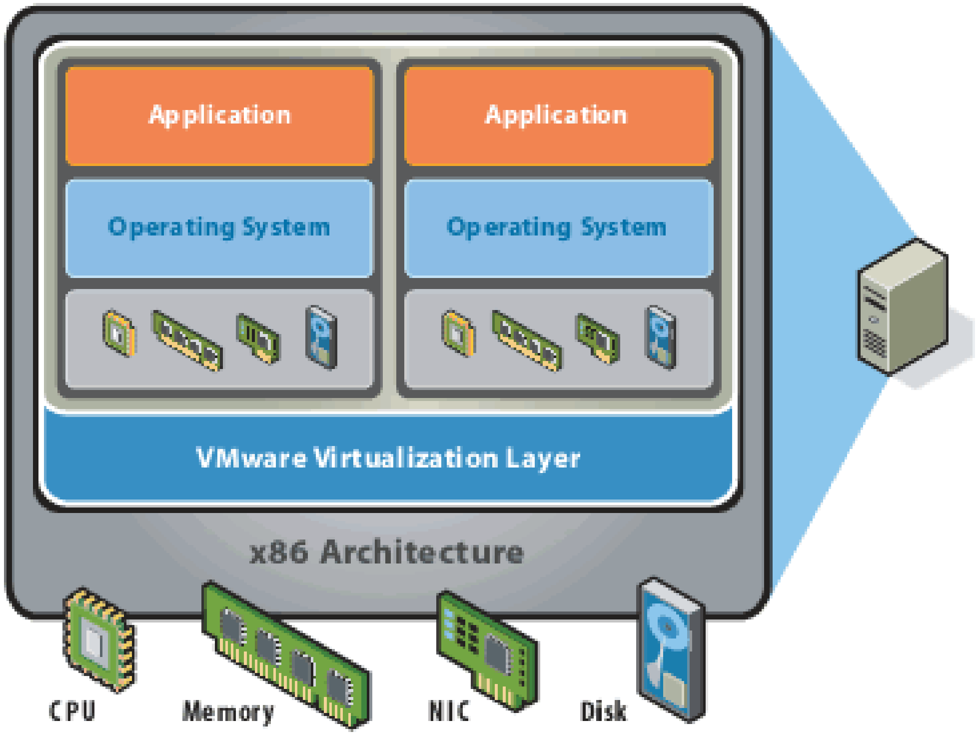
BlackHat USA 2009, Las Vegas

Introduction

VMware Architecture

KNOWING YOU'RE SECURE



Devices are emulated on the Host

Why devices?

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- I don't have enough low-level system Mojo ☹
- They are common to all VMware products
- They “run” on the Host
  - vmware-vmx process
- They can be accessed from the guest
  - Through Port I/O or memory-mapped I/O
- They are written in C/C++
- They sometimes parse some complex data!

Devices on a VM

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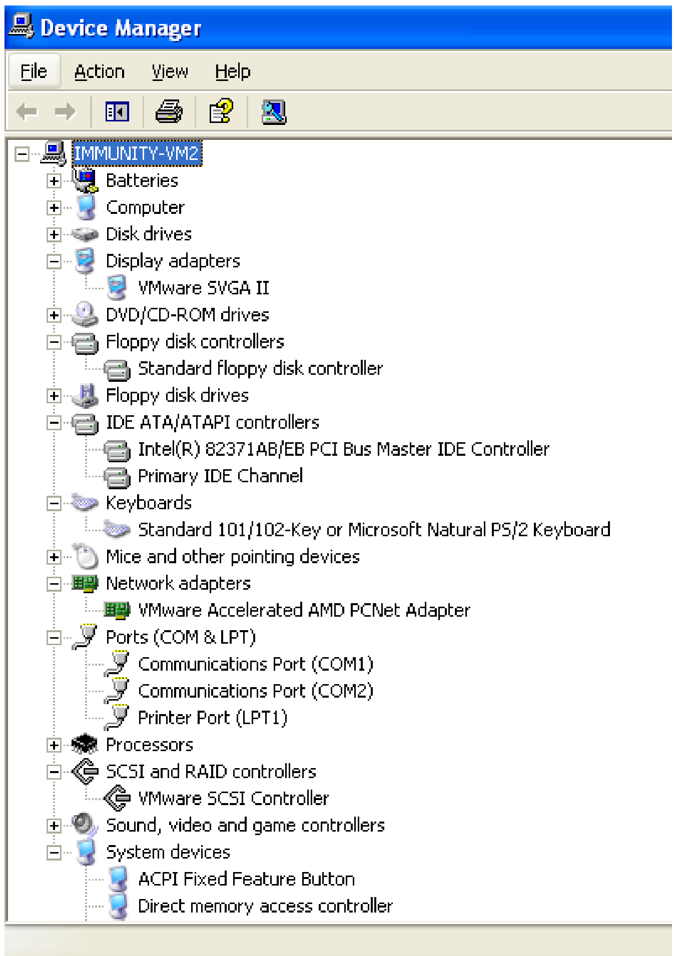

Windows XP SP3 (ESX)

1. **Video adapter**
2. Floppy controller
3. IDE controller
4. Keyboard controller
5. Network Adapter
6. COM/LPT controller
7. SCSI controller(s)
8. DMA controller
9. ~~USB controller (WKS)~~
10. ~~Audio adapter (WKS)~~

CLOUDBURST

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- Combination of 3/4 bugs in the VMware emulated video device
  - Host memory leak into the Guest
  - Host arbitrary memory write from the Guest
    - Relative
    - Absolute
  - And some additional DEP friendly goodness
- Reliable Guest to Host escape on recent VMware products: Workstation, Fusion?, ESX Server (4.0 RC Hardfreeze)

VMware SVGA II

VMware Publications

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- GPU Virtualization on VMware's Hosted I/O Architecture by Micah Dowty, Jeremy Sugerman
  - We were not aware of this paper during our research
  - Good insight on the technology
- Previous VMware security announcements have included device driver guest->host vulnerabilities, as have Microsoft VirtualServer and Xen
- I am not a virtualization specialist

VMware SVGA II

KNOWING YOU'RE SECURE

- VMware virtual GPU takes the form of an emulated PCI device
  - VMware SVGA II
  - No physical instance of the card exists
- A device driver is provided for common Guests
  - Windows ones support 3D acceleration
- A user-level device emulation process is responsible for handling accesses to the PCI configuration and I/O space of the SVGA device

SVGA Device Architecture

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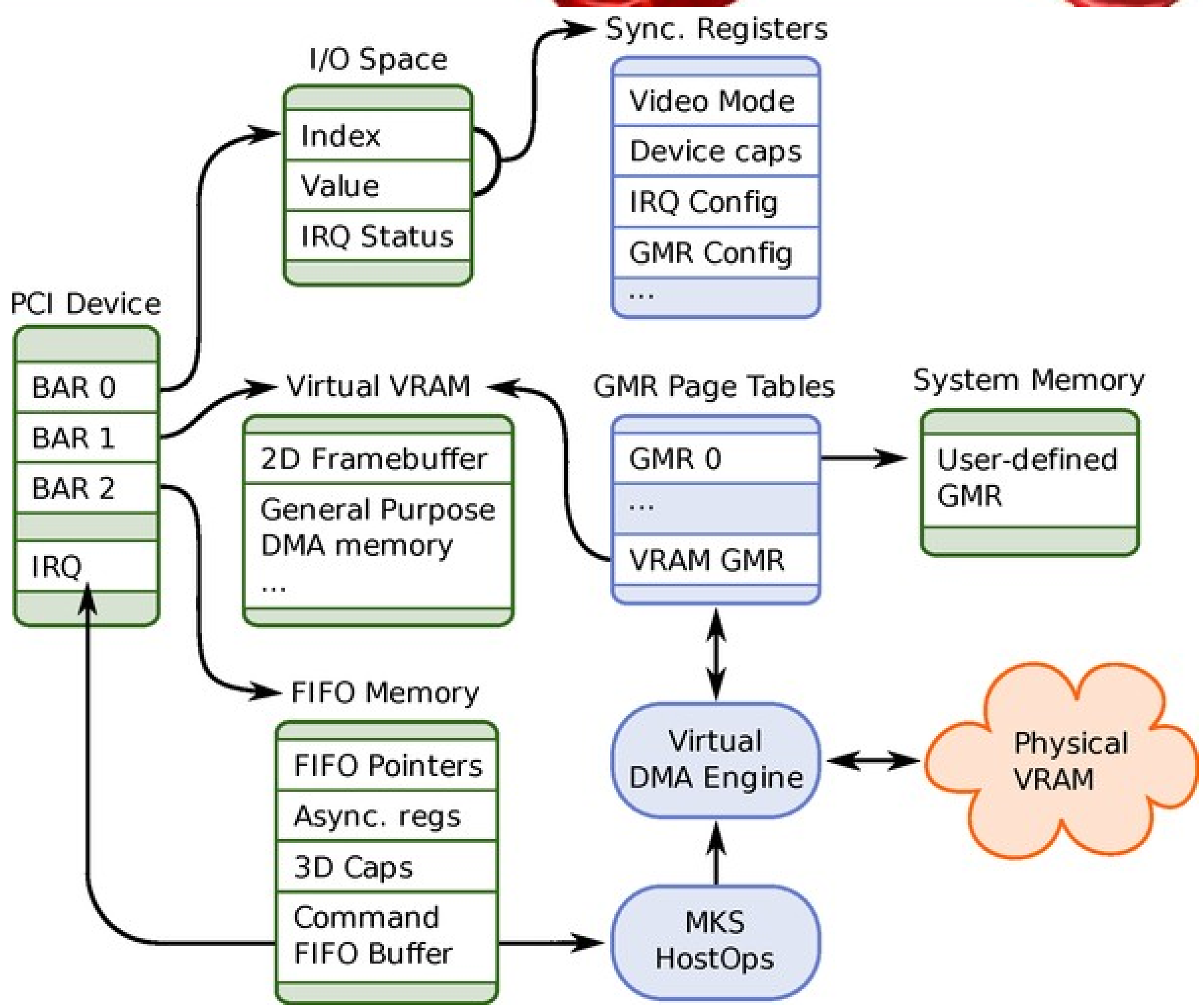

http://www.usenix.org/event/wiov08/tech/full_papers/dowty/dowty.pdf

The Virtual Graphic Stacks

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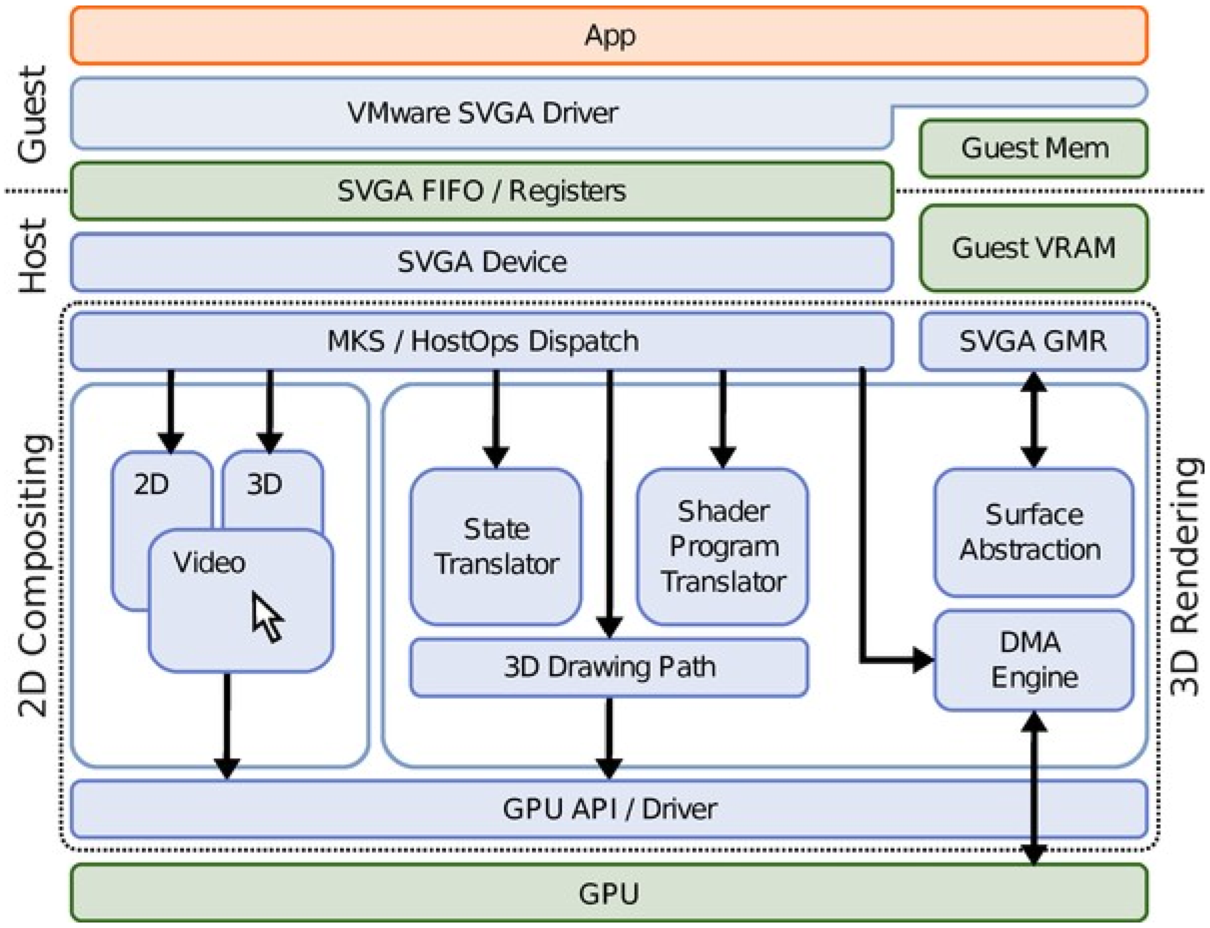

http://www.usenix.org/event/wiov08/tech/full_papers/dowty/dowty.pdf

Memory-mapped I/O

(from Wikipedia)

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- *Memory-mapped I/O* (MMIO) and *port I/O* (also called port-mapped I/O or PMIO) are two complementary methods of performing input/output between the CPU and peripheral devices in a computer
  - Each I/O device monitors the CPU's address bus and responds to any CPU's access of device-assigned address space
  - Port-mapped I/O uses a special class of CPU instructions specifically for performing I/O

My Simplified Version

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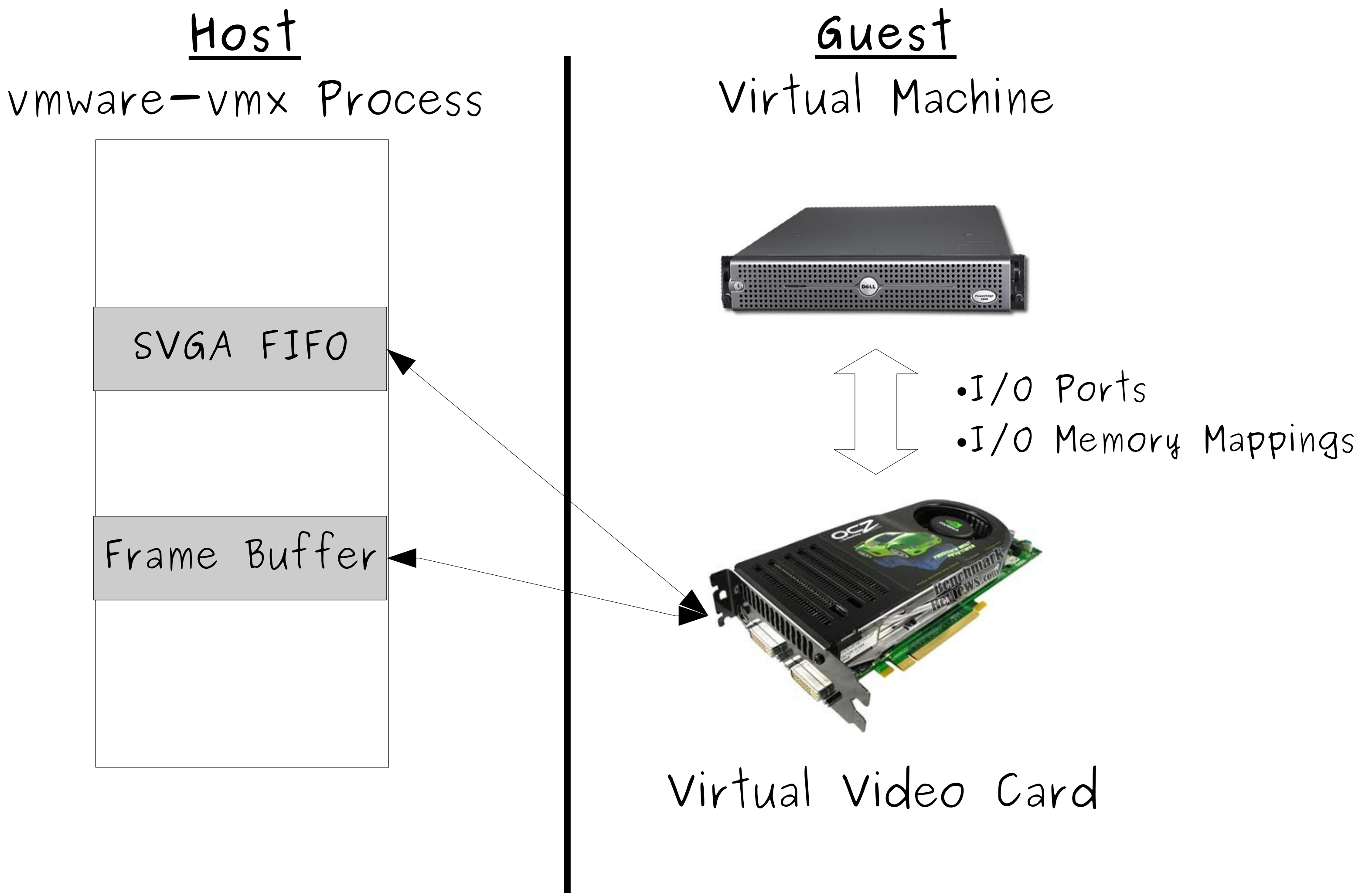
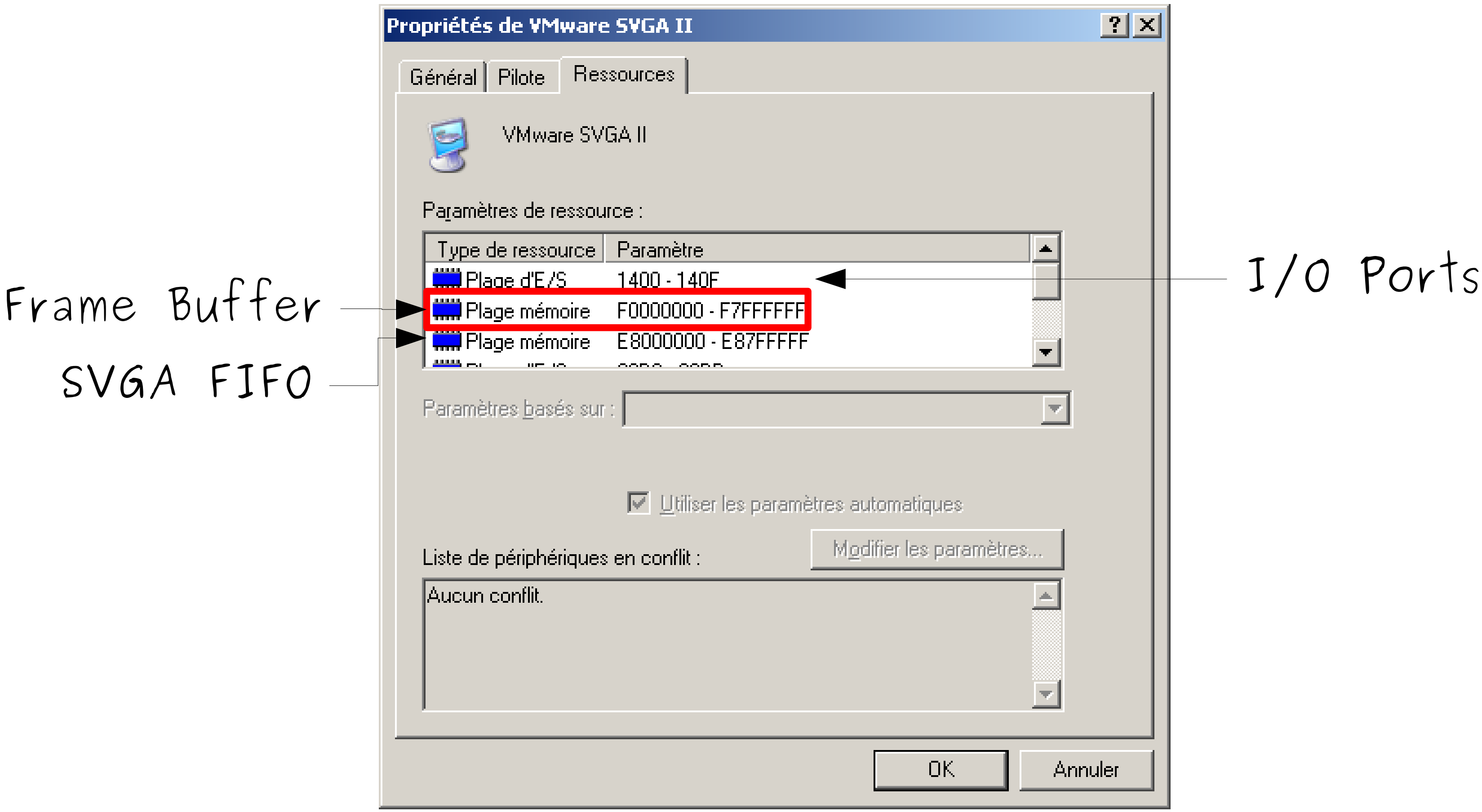


VMware SVGA I/O



Windows 2003 SP1 (WKS)

SVGA FIFO

SVGA FIFO

- The SVGA device processes commands asynchronously via a lockless FIFO queue
  - This queue (several MB) occupies the bulk of the FIFO Memory region
- During unaccelerated **2D** rendering: FIFO commands are used to mark changed regions in the frame buffer
- During **3D** rendering: the FIFO acts as a transport layer for an architecture independent SVGA3D rendering protocol

2D FIFO Operations

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- They can be found in xf86-video-vmware
- Sample 2D operations:
  - SVGA_CMD_UPDATE (1)
    - FIFO layout: X, Y, Width, Height
  - SVGA_CMD_RECT_FILL (2)
    - FIFO layout: Color, X, Y, Width, Height
  - SVGA_CMD_RECT_COPY (3)
    - FIFO layout: Source X, Source Y, Dest X, Dest Y, Width, Height
  - ...

SVGA FIFO 2D Operations

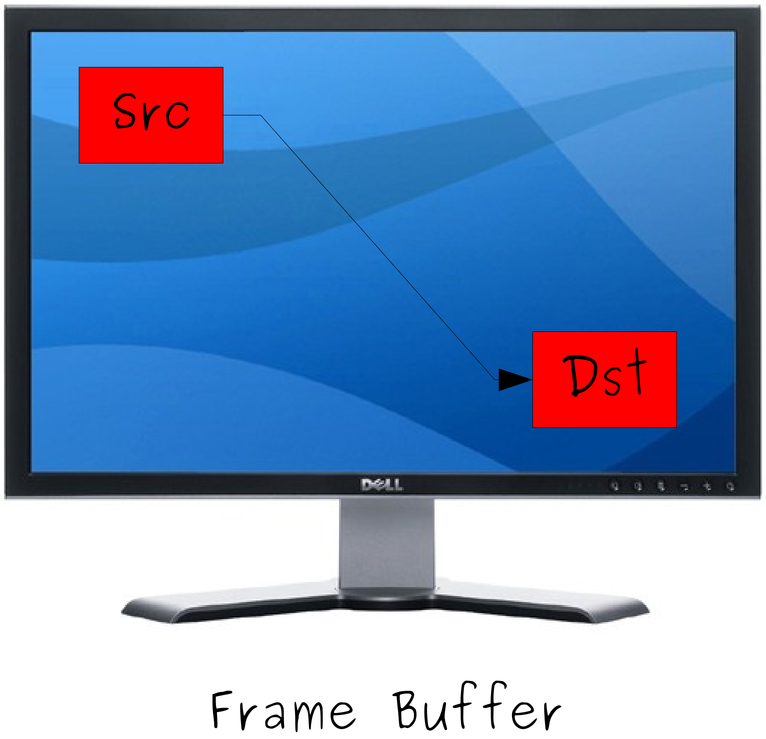
KNOWING YOU'RE SECURE

SVGA_CMD_INVALID_CMD
SVGA_CMD_UPDATE
SVGA_CMD_RECT_FILL
SVGA_CMD_RECT_COPY
~~SVGA_CMD_DEFINE_BITMAP~~
~~SVGA_CMD_DEFINE_BITMAP_SCANLINE~~
~~SVGA_CMD_DEFINE_PIXMAP~~
~~SVGA_CMD_DEFINE_PIXMAP_SCANLINE~~
~~SVGA_CMD_RECT_BITMAP_FILL~~
~~SVGA_CMD_RECT_PIXMAP_FILL~~
~~SVGA_CMD_RECT_BITMAP_COPY~~
~~SVGA_CMD_RECT_PIXMAP_COPY~~
~~SVGA_CMD_FREE_OBJECT~~
SVGA_CMD_RECT_ROP_FILL
SVGA_CMD_RECT_ROP_COPY
~~SVGA_CMD_RECT_ROP_BITMAP_FILL~~
~~SVGA_CMD_RECT_ROP_PIXMAP_FILL~~
~~SVGA_CMD_RECT_ROP_BITMAP_COPY~~
~~SVGA_CMD_RECT_ROP_PIXMAP_COPY~~
SVGA_CMD_DEFINE_CURSOR
~~SVGA_CMD_DISPLAY_CURSOR~~
~~SVGA_CMD_MOVE_CURSOR~~
SVGA_CMD_DEFINE_ALPHA_CURSOR
SVGA_CMD_DRAW_GLYPH
SVGA_CMD_DRAW_GLYPH_CLIPPED
SVGA_CMD_UPDATE_VERBOSE
SVGA_CMD_SURFACE_FILL
SVGA_CMD_SURFACE_COPY
SVGA_CMD_SURFACE_ALPHA_BLEND
SVGA_CMD_FRONT_ROP_FILL
SVGA_CMD_FENCE
SVGA_CMD_VIDEO_PLAY_OBSOLETE
SVGA_CMD_VIDEO_END_OBSOLETE
SVGA_CMD_ESCAPE

SVGA_CMD_RECT_COPY

KNOWING YOU'RE SECURE

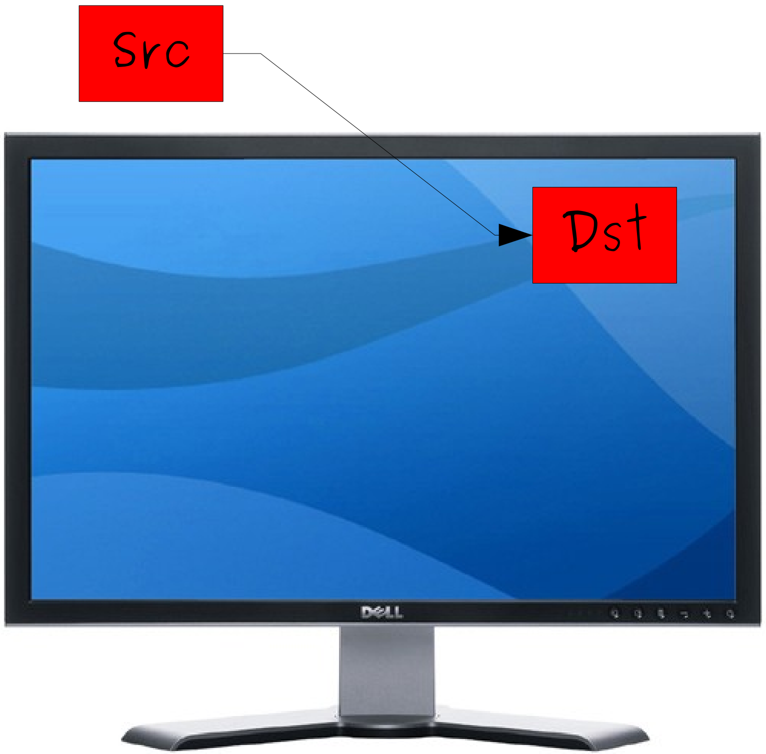
- Copies a rectangle in the Frame Buffer from a source X, Y to a destination X, Y



SVGA_CMD_RECT_COPY

KNOWING YOU'RE SECURE

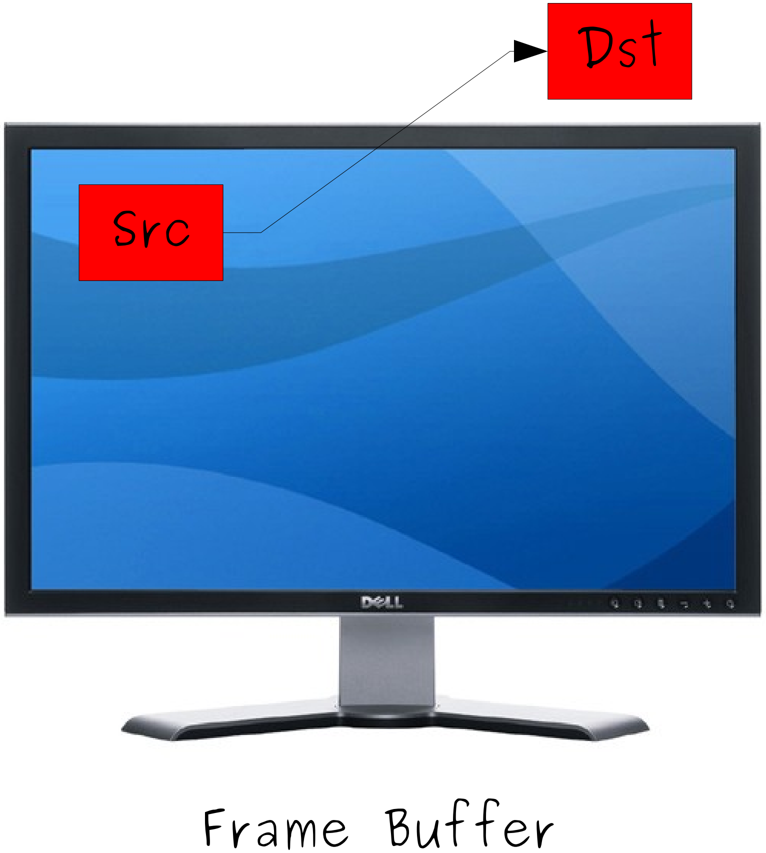
- Boundaries checks on the source location can be bypassed



Frame Buffer

SVGA_CMD_RECT_COPY

- Boundaries checks on the destination location can be bypassed (to a lower extent than source)



SVGA Arbitrary Read&Write

KNOWING YOU'RE SECURE

- Guest can *read* and *write* in the frame buffer
- Frame buffer is mapped in the host memory
- SVGA_CMD_RECT_COPY bugs mean:
  - One can copy host process memory into the frame buffer and read it
    - **Default unlimited arbitrary read**
  - One can write data into the frame buffer and copy it into the host process memory
    - **Default limited arbitrary write**
      - Only into the page preceding the frame buffer
      - *Might* be exploitable in some cases
        - Depends on what is mapped before the frame buffer

SVGA_CMD_DRAW_GLYPH

KNOWING YOU'RE SECURE

- Draws a glyph into the frame buffer
- Requires `svga.yesGlyphs="TRUE"`

Virtual Screen

SVGA_CMD_DRAW_GLYPH

- There is no check on the X, Y where the glyph is to be copied

Virtual Screen

Arbitrary WriteN

KNOWING YOU'RE SECURE

- Frame buffer is mapped in the host memory
- SVGA_CMD_DRAW_GLYPH bug means:
  - One can write any data, anywhere in the host process memory
    - Write address is relative to the base of the frame buffer
      - Pretty steady in ESX
      - Can be leaked with SVGA_CMD_RECT_COPY bug
    - **Non-default arbitrary write**
      - Fully exploitable

VMware & 3D

KNOWING YOU'RE SECURE

- Experimental 3D support appeared in VMware Workstation 5.0 (April 2005)
  - Disabled by default
  - Option had to be added to the config file of the VM
- It became **default** with Wks 6.5 (and Fusion?)
  - "*Accelerate 3D Graphics*" checkbox under Display
    - Code is reachable regardless of checkbox
- 3D operations are default and parsed under ESX 4.0 RC Hardfreeze

SVGA3D

- The SVGA3D protocol is a simplified and idealized adaptation of the Direct3D API
- It has a minimal number of distinct commands
- It is not publicly documented (AFAIK)
  - xf86-video-vmware has definitions for some constants but no prototypes of functions
- It uses “contexts” like Direct3D
  - Stored on the Host
  - Hold render states, light data, etc.

SVGA FIFO 3D Operations

KNOWING YOU'RE SECURE

SVGA_CMD_SURFACE_DEFINE
SVGA_CMD_SURFACE_DESTROY
SVGA_CMD_SURFACE_COPY
SVGA_CMD_SURFACE_DOWNLOAD
SVGA_CMD_SURFACE_UPLOAD
SVGA_CMD_INDEX_BUFFER_DEFINE
SVGA_CMD_INDEX_BUFFER_DESTROY
SVGA_CMD_INDEX_BUFFER_UPLOAD
SVGA_CMD_VERTEX_BUFFER_DEFINE
SVGA_CMD_VERTEX_BUFFER_DESTROY
SVGA_CMD_VERTEX_BUFFER_UPLOAD
SVGA_CMD_CONTEXT_DEFINE
SVGA_CMD_CONTEXT_DESTROY
SVGA_CMD_SETTRANSFORM
SVGA_CMD_SETZRANGE
SVGA_CMD_SETRENDERSTATE
SVGA_CMD_SETRENDERTARGET

SVGA_CMD_SETTEXTURESTATE
SVGA_CMD_SETMATERIAL
SVGA_CMD_SETLIGHTDATA
SVGA_CMD_SETLIGHTENABLED
SVGA_CMD_SETVIEWPORT
SVGA_CMD_SETCLIPPLANE
SVGA_CMD_CLEAR
SVGA_CMD_PRESENT
SVGA_CMD_DRAWPRIMITIVES
SVGA_CMD_DRAWINDEXEDPRIMITIVES
SVGA_CMD_SHADER_DEFINE
SVGA_CMD_SHADER_DESTROY
SVGA_CMD_SET_VERTEXSHADER
SVGA_CMD_SET_PIXELSHADER
SVGA_CMD_SET_SHADER_CONST
SVGA_CMD_DRAWPRIMITIVES2
SVGA_CMD_DRAWINDEXEDPRIMITIVES2

3D Bugs

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- Many SET commands are flawed
- SETRENDERSTATE
  - The code:

```
.text:0065EE25
.text:0065EE25 loc_65EE25: ; CODE XREF: SetRenderStateInContext+25j
.text:0065EE25 mov edi, [ecx+eax*8]   ; Offset @ InputData[i]
.text:0065EE28 mov ebx, [ecx+eax*8+4] ; Data @ InputData[i+1]
.text:0065EE2C add eax, 1             ; i++
.text:0065EE2F cmp eax, edx
.text:0065EE31 mov [esi+edi*4+50h], ebx
.text:0065EE35 jb short loc_65EE25
```

  - Write primitive relative to **`esi`**
    - It's the context address in the host memory
    - It can be leaked in the guest thanks to the COPY bug!

Relative to Absolute

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- SETLIGHTENABLED
  - The code:

```
.text:0065EF33 mov ecx, [ebp+arg_4]
.text:0065EF36 mov eax, [ecx+4]
.text:0065EF39 mov ecx, [ecx+8]
.text:0065EF3C mov edx, eax
.text:0065EF3E shl edx, 4
.text:0065EF41 sub edx, eax
.text:0065EF43 mov eax, [ebp+arg_0]
.text:0065EF46 mov eax, [eax+648h]
.text:0065EF4C mov [eax+edx*8], ecx
```

  - By overwriting Context+648h with the relative write, we get an absolute write primitive
  - Also works with SETLIGHTDATA for 29*4 bytes

Moar Bugz

- Additional bugs in:
  - SETRENDERTARGET
    - Signed bounds checking
  - SETCLIPPLANE
    - No bounds checking
  - SETTRANSFORM
    - No bounds checking

Exploitation

Requirements

KNOWING YOU'RE SECURE

- We have to be able to read/write directly into the framebuffer and the FIFO
  - Direct3D has some APIs for that
    - Everything is checked and sanitized on the Guest side
  - The solution is to write our own driver
    - Sits on top of VMware video driver
      - It can be standalone though
      - Less coding to do this way
    - Maps the framebuffer and FIFO for direct, unrestricted access
- Requires Admin rights in the VM

Exploitation Process

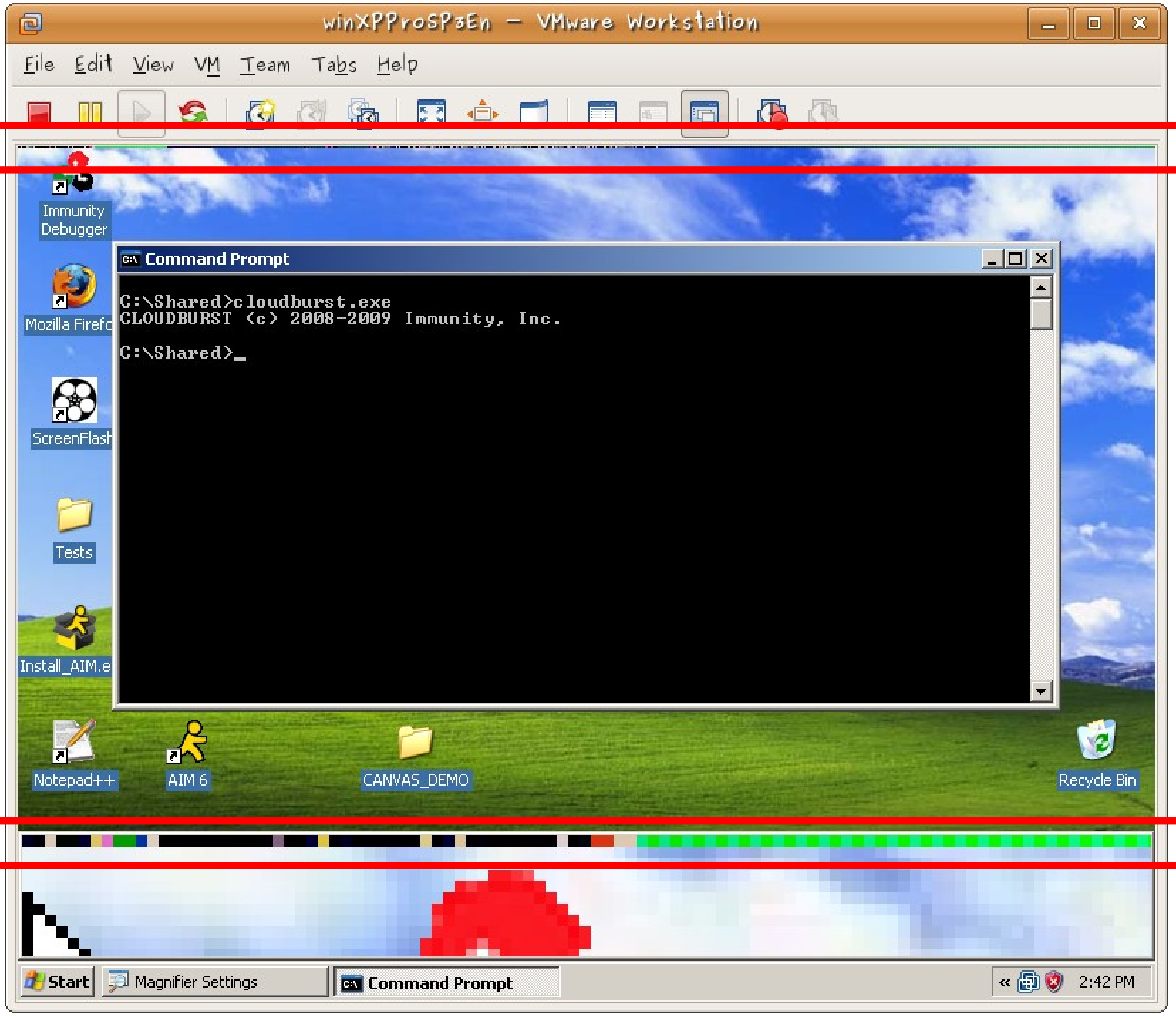
KNOWING YOU'RE SECURE

- **Step #1**: leak the base address of the framebuffer in the Host
  - All further leaks are relative to this address
- Some methods:
  - Windows Vista: relative memory leak
    - The page before the FB contains the address of the FB
  - Ubuntu: relative leak bruteforce
    - Keep leaking until your find the ELF header
  - Windows XP/Vista: absolute memory write
    - Then scan the FB for the data written
    - The FB is big enough to not trigger an access violation

Exploitation Process

- **Step #2**: fingerprint VMware version
  - We leak the PE/ELF header for that
    - They tend to be always at the same address
- **Step #3 to #n**: exploit ☺
  - Leak/Overwrite/Trigger/Leak/Overwrite/Trigger – Done!

Leak Example



We leak some data on the first line of the framebuffer (more visual)

Dealing with DEP

KNOWING YOU'RE SECURE

- When dealing with XP/Vista DEP AlwaysOn, or ESX 4.0 as a Host, we have to care about NX
- vmware-vmx provides VirtualProtect wrappers
  - One for RE, one for RW
  - They take their parameters in the .data section!
    - Easily abusable with the absolute write primitive
  - Also available for mprotect under Linux/ESX

Vista 12 Steps Example: 1 to 6

KNOWING YOU'RE SECURE

1) **Leak** the Frame Buffer Base address in the Host
2) **Leak** the PE Header of the vmware-vmx.exe binary
3) Based on the Timestamp in the PE Header, set the correct addresses needed
4) **Leak** the 1st pointer of the theSVGAUser structure
5) **Leak** the memory pointed by the leaked pointer to retrieve the address of the Context
6) **Overwrite** the VirtualProtect parameters so that the address is the one of the PE header and the size is 1000h. **Overwrite** as well the function pointer for the ESCAPE command with the address of the RW VirtualAlloc wrapper

Vista 12 Steps Example: 7 to 12

KNOWING YOU'RE SECURE

1) **Trigger** the ESCAPE command: the PE Header is now RW
2) **Write** the shellcode into the PE Header
3) Same as 6), except that we overwrite the ESCAPE function pointer with the RE VirtualAlloc wrapper
4) **Trigger** the ESCAPE command: the PE Header (and our shellcode) is now RE
5) **Overwrite** the ESCAPE function pointer with a pointer to our shellcode.
6) **Trigger** the ESCAPE command

MOSDEF Over Direct3D

(or how to tunnel a shell over BMP images)

MOSDEF

- MOSDEF (mose-def) is short for “Most Definately”
- MOSDEF is a retargetable, position independent code, C compiler that supports dynamic remote code linking written in pure Python
- In short, after you've overflowed a process you can compile programs to run inside that process and <u>report back to you</u>

Post Exploitation

KNOWING YOU'RE SECURE

- Ensure Host ⇔ Guest communication post exploitation, while not relying on extra features such as:
  - Network: Host can be unreachable from Guest
  - VMCI: not enabled by default
  - VMRPC: can be disabled
- Idea: tunnel the shell over the framebuffer
  - And in Ring3 to add some excitement

Guest Side: Direct3D API

KNOWING YOU'RE SECURE

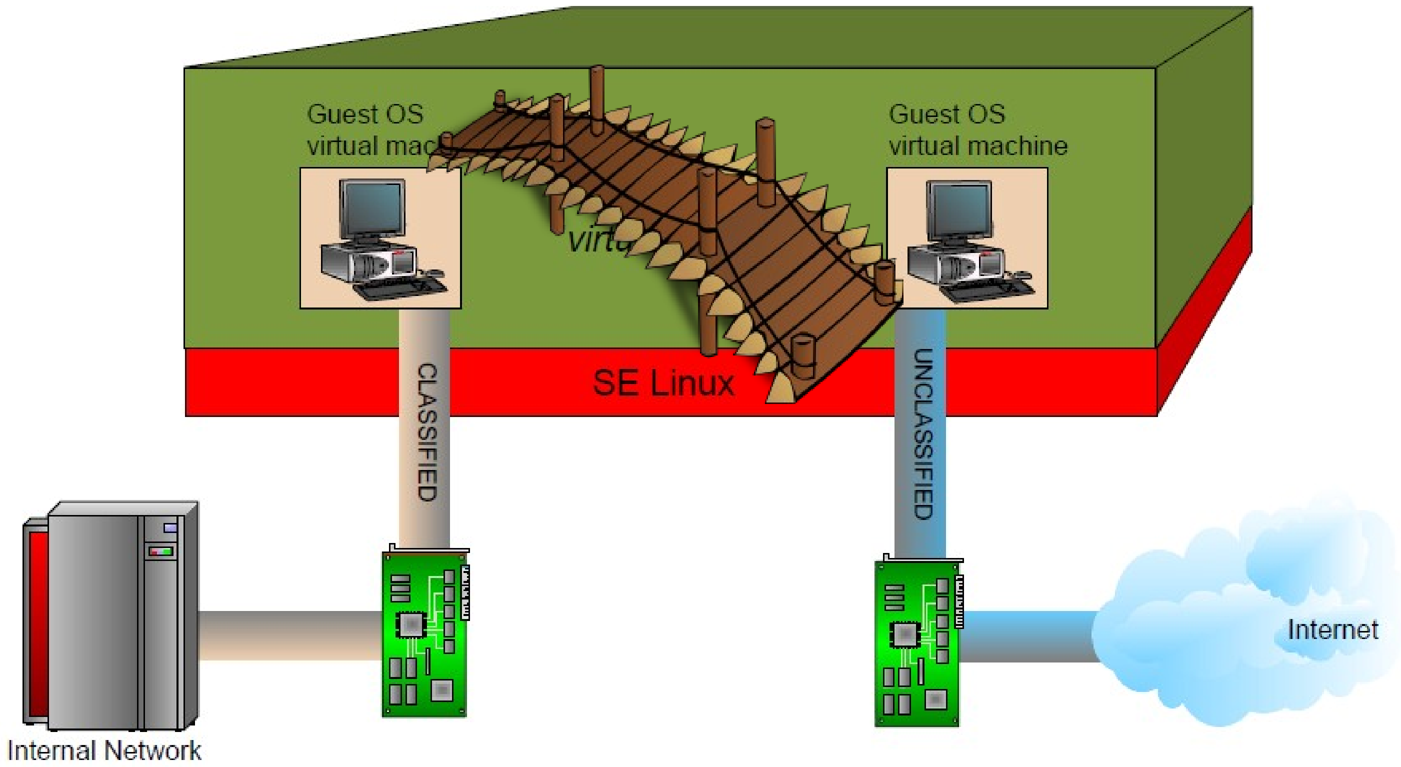
- Create and manipulate objects (surfaces) in the video card memory, off screen
  - CreateOffscreenPlainSurface
    - Format being D3DFMT_A8R8G8B8 (32 bits per pixel)
  - D3DXLoadSurfaceFromMemory
  - D3DXSaveSurfaceToFileInMemory
    - No “raw” format, use D3DXIFF_BMP
    - We parse the BMP to recover our data

Host Side

KNOWING YOU'RE SECURE

- Bind a MOSDEF listener on localhost
- Scan the video card memory for a “signature”
  - Extract and parse the data
  - Send it to the locally bound MOSDEF
  - Receive the result
  - Write it back to the framebuffer
- MOSDEF acting sequentially, we should not have any concurrent access issue
  - We implement a lousy “semaphore” to be sure

The Result



“Virtual Wooden Bridge”

over the

“Virtual Air Gap”

Conclusion

Who am I

- Title
  - Sr. Director VRT
- Industry Experience
  - 13+ Years
- Previous Companies
  - Farm9, Hiverworld (nCircle), IBM
- Certifications
  - I'll send you a PDF with all my credits, certs, and previous work. I'd open it in a VM.

☺

4

SOURCEfire
Security for the real world.

Virtualization Misconceptions

KNOWING YOU'RE SECURE

- VMware isn't an additional security layer
  - It's just another layer to find bugs in
- Given the correct bug primitives (memory leak, memory write), everything can be defeated
  - ASLR, NX
- Trying to patch silently in 2009 is ridiculous
- If a feature is not needed for a branch, the code shouldn't be included in it
  - Why would ESX ever need 3D support ...