

Next Class (Sep 17): Checkpoint-1

online score sheet

What we are trying to figure out:

- Are you clear on the problem being addressed?
- Have you broken up the work into small steps?
- Are you realistic about how long each step will take?
- Will you need any special resources
(e.g. hardware, cloud resources, cloudlet resources, etc.)?
- Do you know how to acquire these resources?
- Do you have a good sense of what might go wrong?
- Do you have backup plans if Murphy strikes?
- *Have you gotten your hands dirty yet?*

2 projects

~30 minutes per project

Encourage mentors to attend

Leveraging Virtual Machines in Mobile Computing

15-821 / 18-843
Fall 2024

Mahadev Satyanarayanan
School of Computer Science
Carnegie Mellon University

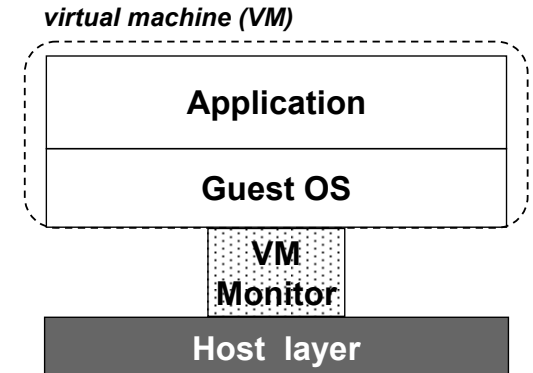
What is a Virtual Machine?

VM = *perfect software abstraction of OS-visible hardware*

A virtual machine monitor (VMM) implements the VM abstraction

- **software layer between OS and hardware**
- **functionally invisible to OS and apps**
(timing tests may reveal presence of VM)
- **able to multiplex hardware among multiple VMs**

VMM is also referred to as a “hypervisor”



Roots of VM Technology

“Victory has a thousand fathers, defeat is an orphan”

(John F. Kennedy, 1961)

- roots of today’s VMs reach back to 1960s

M44/44X (IBM), CTSS (MIT), {CP-40, CP-67, CP/CMS} (IBM) ... VM/370 (IBM product, 1972)

- what was the driving force?

Hardware very expensive (mainframes)

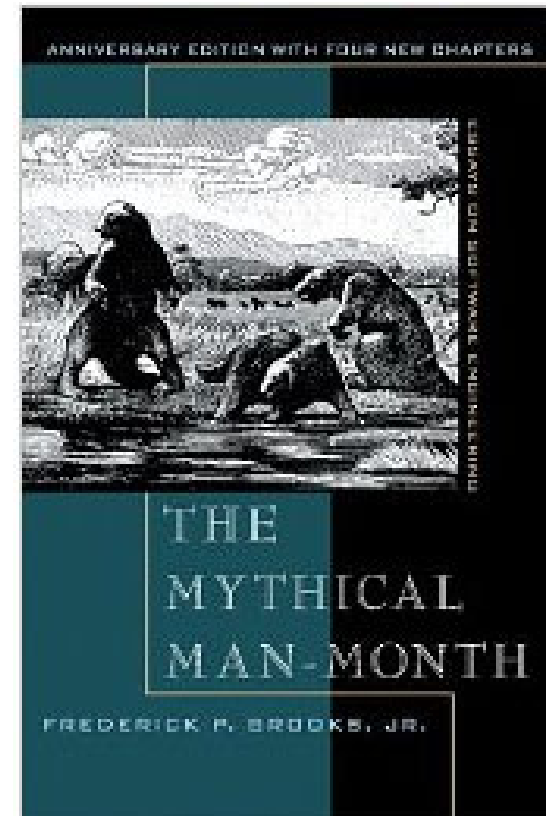
Explosion of effort in low-level system software

Pain point: need real hardware for testing

“nearly identical” not good enough

Hardware virtualization wins big

- enhances productivity of system software development
- new software runs concurrently with older versions



Fred Brooks, Jr.

1999 ACM Turing Award

The Strange History of VMs

mid-1960s to early 1970s	birth and emergence
early 1970s to late 1970s	extensive commercial use (VM/CMS)
late 1970s to early 1980s	emergence of personal computers (IBM PC 1981)
late 1980s to late 1990s	“demise” of VMs
late 1990s	rebirth of VMs (VMware)
early 2000s	resurgence of research interest in VMs
late 2000s to present	explosion of commercial interest (cloud computing)
... <i>the future</i> ...	????
...2022....	Lightweight forms of VM-like abstractions “ <i>Docker</i> ”, “ <i>Containers</i> ”, “ <i>Intel Clear Containers</i> ”, ...

What is the Secret?

What accounts for the longevity of the VM abstraction?

Pain points have shifted over ~50 years,

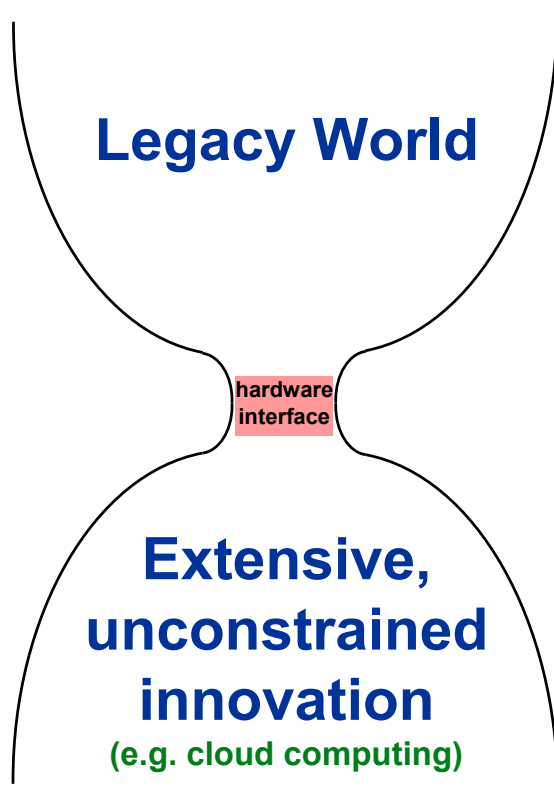
In each case, VM-based solutions have relieved pain while

- 1. preserving legacy investments*
- 2. remaining robust, stable, easy to deploy*

Note that

- **exact form of legacy investment may vary**
application software, system software, enterprise workflows, user learning/culture, ...
- **focus on hardware virtualization** (of near-perfect fidelity)
not para-virtualization, not language VMs (e.g. JVM)

Why Is Hardware Special?



Narrow & stable waistline critical

- narrow → freer innovation
- narrow → vendor neutrality
- stable → longevity / ubiquity

Alas, waistlines expand over time

- new features/functionality
- undocumented features

Software too malleable!

A Cautionary Lesson

Wide interfaces → external complexity → *brittle abstractions*

- Hard to deploy, hard to sustain, hard to scale

Process migration

- 1983 to 2011, PhD theses roughly every 5 years
- not supported by any production OS today (open or closed)
- great idea whose time has never come!

Contrast the wild real-world success of VM migration

- VMs are a key enabler of cloud computing
- widely used production-quality implementations

Why are VMs relevant to mobile computing?

They are big and clunky, hardly the picture of mobility!

To see their relevance, we'll need to first take a slight detour ...

Plummeting cost of hardware

September 2024



10.1inch Android netbook, portable laptop with A133P CPU, 2GB RAM 64GB Rom 800x1280 IPS Screen (Blue)

Brand: EVRAIN
3.3 ★★★★★ 46 ratings | Search this page

Price: **\$99.99** ✓prime Two-Day
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Color: Blue

Brand: EVRAIN
Model Name: HL-1016M
Screen Size: 10.1 inches
Color: Blue
Hard Disk Size: 64 GB
CPU Model: A110
Ram Memory: 2 GB



Dell Chromebook 13 3380 6TXJ4 13.3-Inch Traditional Laptop (Black)

Visit the Dell Store
3.8 ★★★★★ 24 ratings | Search this page

Price: \$130.43
Business Price **\$129.57**
You Save: \$0.86 (1%)

CPU: Celeron C3855

Brand: Dell
Model Name: Dell 3380 13" Chromebook Celeron 3855U 4GB 32GB
Screen Size: 13.3 Inches
Color: Black
Ram Memory: 4 GB
Installed Size: 32 GB
Operating System: Chrome OS

See more

About this item

- Intel Celeron C3855 Processor; 4GB Memory; 16GB SSD
- 13.3 HDF Non-Touch LCD
- 10 hours of battery life
- 1 Year Mail in Service

See more product details

Top reviews for business

Buy new: **\$129.57**

FREE delivery **Wednesday, September 18.** Details

Deliver to Carnegie - Pittsburgh 15213

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Return policy: 30-day refund/replacement ▼

Add a Protection Plan:



ASUS 15 Slim Chrome OS Laptop Intel Processor up to 2.4GHz 15.6in Full HD NanoEdge-Display with 180 Degree-Hinge 4GB DDR4 32GB Storage WiFi + BT (C523 - Renewed)

Visit the ASUS Store
4.1 ★★★★★ 69 ratings | Search this page

Price: **\$119.99**

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Capacity: 4GB 32GB - FHD

4GB 32GB - FHD 4GB 64GB - FHD

Color: Silver

Brand: ASUS



Fusion5 14.1inch A90B+ Pro 64GB Windows 10 Laptop - 4GB RAM, 64GB Storage, Full HD IPS, Bluetooth, 2MP Webcam, Dual Band WiFi

Brand: Fusion5
3.8 ★★★★★ 1,815 ratings | Search this page

Price: **\$134.95** ✓prime
FREE Returns ▼

Brand: Fusion5
Model Name: A90B+PRO-64GB
Screen Size: 14.1 Inches
Color: Grey
Hard Disk Size: 64 GB
CPU Model: Celeron N3350
Ram Memory: 4 GB

See more

About this item

- Terrific Download and Upload Speeds: A90B+ Pro Windows Laptop PC features 5 GHz WiFi which means the download and upload speeds are atleast 2x faster than traditional laptops. Furthermore, our A90B+ pro is designed such that it can handle complex tasks with ease. A90B+ pro (v2) is 135% faster than our T90B+ pro (v1) according to benchmark tests.

September 2023



UNXAI Laptop Computer 14inch Student Laptop Computer Intel Celeron N3350 Windows Laptop 4GB RAM 64GB Storage School Laptop Computer for Students and Business High-Performance Laptop (Silver)

4.2 ★★★★★ 7 ratings

Price: \$145.99

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Color: Silver

\$145.99 \$145.99



14.1" Windows 11 Laptop, Intel Celeron N3350, 1920x1080 FHD IPS Display, Ultra Slim Notebook PC, with 4GB RAM 64GB EMMC BT4.2, Work Study Computers

Brand: WAKST

Price: \$159.99 prime Two-Day FREE Returns

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Capacity: 146-N3350

146-N3350	146-N3450-192GB	1308-N4120-4GB	1308-N5100
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10.1 inch Mini Laptop, HD Notebook PC with Dual Cores Processor, 64G ROM, Rich Expansion Slots, for Windows System, for Daily Work and Entertainment (US Plug 3G+64G)

Brand: Serounder

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Capacity: US Plug 3G+64G

US Plug	US Plug
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Yoidesu 10.1 Mini Laptop, Win10 Portable Education Laptop Notebook Computer, 2.4GHz

Yoidesu 10.1 Mini Laptop, Win10 Portable Education Laptop Notebook Computer, 2.4GHz Dual Core for N3350 CPU 64G ROM Ultra Thin Notebook for Office Travel Home, 2500mAh WiFi BT (US 3G+64G)

Visit the Yoidesu Store

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Capacity: US 3G+64G

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Recommendations (0 of 10)

September 2022

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Highlight: None








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Recommendations (0 of 10): ON

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Products					
	 <p>ThinkPad X Series X131e (33722WU) AMD E-300 1.30GHz 2GB Memory 320GB HDD 11.6" Notebook Windows 8 Pro 64-bit</p> <p>ADD TO CART</p> <p>ADD TO WISH LIST</p> <p>\$152⁸⁸ Free Shipping</p>	 <p>Lenovo 14e Chromebook 81MH0006US 14" LCD Chromebook - AMD A-Series A4-9120 Dual-core (2 Core) 1.60 GHz - 4 GB LPDDR4X - 3...</p> <p>ADD TO CART</p> <p>ADD TO WISH LIST</p> <p>\$199⁰⁰ Special Shipping</p>	 <p>DELL Laptop Inspiron 14 i3452-5600BLK Intel Celeron N3050 (1.60 GHz) 2 GB Memory 32 GB SSD Intel HD Graphics 14.0" Windows 10...</p> <p>ADD TO CART</p> <p>ADD TO WISH LIST</p> <p>\$199⁹⁷ Free Shipping</p>	 <p>HP 11a Chromebook School and Business Laptop Black (Intel Celeron N3350 2-Core, 4GB RAM, 32GB SSD, 11.6" HD (1366x768), Intel HD 500, Wi...</p> <p>ADD TO CART</p> <p>ADD TO WISH LIST</p> <p>\$209⁰⁰ Special Shipping</p>	 <p>Hyundai Thinnote L14WB2BK 14.1" Celeron Laptop 4GB/64GB + HDD Slot Win 10 Home S Mode Black</p> <p>ADD TO CART</p> <p>ADD TO WISH LIST</p> <p>\$229.99 \$228⁹⁹ Free Shipping</p>
Rating			 (1)		 (1)
In Stock	Yes	Yes	Yes	Yes	Yes

2020 was an Outlier

The pandemic has made it harder to buy a new laptop

Outbreaks have combined supply-chain hurdles with spikes in demand

By [Monica Chin](#) | [@mcsquared96](#) | Jun 4, 2020, 8:00am EDT

Covid-19 Effect: Work from Home, online learning push up laptop prices by 30%



[Mahesh Kulkarni](#), DHNS, Bengaluru, JUL 06 2020, 23:35 IST | UPDATED: JUL 07 2020, 08:49 IST

Laptop shortage threatens back-to-school plans as COVID-19 pandemic causes delays

Jocelyn Gecker and Michael Liedtke Associated Press

Published 2:14 p.m. ET Aug. 23, 2020 | Updated 3:49 p.m. ET Aug. 23, 2020



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newegg Business FEEDBACK

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Keywords, Model # or Item #

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September 2019

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Grade A Laptop Dell E4310 I 5 520M 2.4G 4G DDR3 Memory 160G DVD Windows 10 Pro	THOMSON NEO12 Laptop / Intel CPU, 2/32GB / 11.6 Inch / HD 1366x768 / Webcam / Wi-Fi & Bluetooth 4.0 / Keyboard with Multi-touch Pad / Battery up to 7 Hours / Windows 10 Home / Pink, Slim and Light	Ultra Slim 7 Inch Android Notebook Mini Laptop WIFI Android 4.4 1.5GHz 512MB Memory 4G Hard Disk Tablet PC, White Color	Asus Vivobook E203MA Thin and Lightweight 11.6" HD Laptop, Intel Celeron N4000 Processor, 2GB RAM, 32GB eMMC Storage, 802.11AC Wi-Fi, HDMI, USB-C, Win 10	7 Inch notebook Android laptop HDMI Laptop inch Dual Core Android 4.4 VIA 8880 HD MI Wi-fi Mini Netbook Black Color	
\$167.90	\$169.99 \$129.99 Save: 24%	\$180.00 \$130.00 Save: 28%	\$199.00 \$169.00 Save: 16%	\$200.00 \$160.00 Save: 20%	
Free Shipping	Free Shipping	Free Shipping	\$14.50 Shipping	Free Shipping	
Sold by MicroBee	Sold by THOMSON	Sold by Soledpower	Sold by F&W SYN Mark...	Sold by Soledpower	
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September 2014

Product	x Remove	x Remove	x Remove	x Remove
<p>ASUS X551MAV-EB01-B Intel Baytrail-M Dual Core N2830 2.16GHz 15.6" Windows 8.1 64-Bit Notebook</p> <p>\$249.99</p> <p>Free Shipping</p> <p>ADD TO CART</p> <p>ADD TO WISH LIST</p>	<p>Acer Aspire ES1-511-C59V Intel Baytrail-M N2830 2.16GHz 15.6" Windows 8.1 64-Bit Notebook</p> <p>\$249.99</p> <p>Free Shipping</p> <p>View Details</p>	<p>TOSHIBA Satellite C55-B5299 Intel Baytrail-M N2830 2.16GHz 15.6" Windows 8.1 Notebook</p> <p>\$299.99 \$244.99 Save: 18%</p> <p>Free Shipping</p> <p>View Details</p>	<p>ASUS X200MA-DS02 Intel Celeron N2815 1.86GHz 11.6" Windows 8.1 Notebook</p> <p>\$349.99 \$229.99 Save: 34%</p> <p>Free Shipping</p> <p>View Details</p>	

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- High Pressure Laminate Insert
- Choice of Two Laminate Surface Inlays
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Warranty Information

Dimensions - Overall 24"W x 24"D x 20.5"H

Product Weight 32 Lbs

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LSR-F1355T5 Brewster Corner Table

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- 6 Wood Finish Choices
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Warranty Information

Dimensions - Overall 24"W x 24"D x 20.5"H

Product Weight 32 Lbs

Brewster Series, Corner Table - F1355T5

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All Lesro Furniture Ships Free in the contiguous United States!

Item Number: 90130

Manufacturer SKU: F1355T5

Bring sophistication to your reception area with the Brewster Series by Lesro! Decorate or stay organized with the coffee table. It is a great solid center piece that holds anything. The small design makes it easy to put in smaller areas.

List Price: ~~\$439.00~~

Your Price: **\$239.95** (45% savings)

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September 2014



Lesro Brewster Series Reception Furniture; Corner Table

Item # 174-F1355T5
• Table Top Depth: 24" • Table Top Width: 24" • Edge Style: Beveled

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\$214.99

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When you buy 3+

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\$224.99 Total Price

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Lesro Brewster Series Corner Table, 20 1/2"H x 24"W x 24"D, Cherry/Charcoal

Item #426020

★★★★★ (0)



Feedback



\$219.99/each



Item Not Available For Delivery

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Not Available for shipping



Item no longer available

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Due to supply chain shortages, price and availability will require verification.

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Lesro > LSR-F1255T5



LSR-F1255T5 Brewster End Table

Additional Images click to enlarge



Lesro Brewster End Table LSR-F1255T5

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Estimated Shipping: 14 days

- Solid Wood Table
- Stylish Design
- Sturdy Construction
- High Pressure Laminate Insert
- Choice of Two Laminate Surface Inlays
- 6 Wood Finish Choices
- **Corner & Coffee Tables Also Available**

Warranty Information

Dimensions - Overall 20"W x 20"D x 20.5"H

Product Weight 23 Lbs

Options for Lesro LSR-F1255T5

Top Finish

Wood Finish

Add To Cart Quantity:

Takeaway

Portable hardware today is as cheap as simple office furniture

could be provided by space owner (e.g. doctor's office, Starbucks, etc.)

But system administration for an end table is trivial

- **Just wipe it clean**
- **Administering portable hardware is more complex (TCO)**
- **Can we make system administration as simple as “wipe it clean”?**

***How will almost-free hardware
change our world?***

Can lead to hands-free mobile computing

“Carry” vs. “Find”

	Portable	Pervasive
Air		✓
Light	✓	✓
Water	✓	✓
Telephone (pre-2000)	✓	✓
Telephone (post-2000)	✓	✓
Mobile Computing (now)	✓	✓
Personal Computing (future)	?	?

Inherent Duality

Anticipated worst case scenario is determining factor

“Find” ⇒ resource available at all visited locations

“Carry” ⇒ reasonable doubt at least at one location

Ubiquity can substitute for portability → Inherent duality

Can we do this for personal computing? → *Transient PC*

- enables “find” rather than “carry” for personal computing
- hardware found everywhere, just like air/water/light
- perfectly and instantaneously customized to specific user

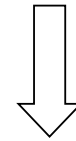
Authoring vs Consumption

Examples of *information authoring*

- software development
- developing architectural plans
- writing a paper or book
- writing a legal brief
- creating animation for a movie
- programming a CNC machine tool
- ...

~85 million ultramobiles sold in 2019
~0.5% of information consumption devices
(but margins larger)

Increasingly, in many domains,
*value creation involves
information authoring*



full function laptop/notebook with
mouse and keyboard needed
tablet or smartphone won't do

Examples of *information consumption*

- web surfing
- watching a YouTube "howto" video
- watching a Netflix movie
- ...

~2 billion tablets + smartphones sold in 2019
(small margins)

How To Create Transient PCs?

VM-based Transient PCs: Two Approaches

Approach 1: *Internet Suspend/Resume (ISR)*

- 2002–2013 at CMU
- “*Pervasive Personal Computing in an Internet Suspend/Resume System*” (2007)
- aka “Post-Copy VM migration”

Approach 2: *VMHandoff* (aka “EdgeVDI”)

- 2017 – now at CMU
- “*You Can Teach Elephants to Dance: Agile VM Handoff for Edge Computing*” (2017)
- aka “Pre-Copy VM migration”

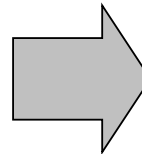
Internet Suspend/Resume[®] System

(<http://isr.cmu.edu>)

ISR-1 late 2001 – early 2002

Proof of concept

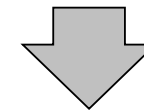
- VMM = VMware Workstation 3.0
- dist. storage = NFS
- copyin/copyout of entire VM state



ISR-2 early 2002 – late 2004

Performance tradeoff exploration

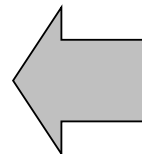
- VMM = VMware Workstation 3.0
- dist. storage = Coda
- loadable kernel module (“fauxide”)
- user-level ISR client (“vulpes”)



OpenISR mid 2006 – 2013 (release 0.10.1)

Production-quality open source system

- VMM-agnostic (VirtualBox, KVM, VMware, ...)
- complete re-engineering of code base
- total rewrite of kernel code (nexus)
- ongoing evolution of client and server functionality and performance
- continuous deep use (~15-20 users)
- PocketISR boot capability



ISR-3 late 2004 – mid 2006

Pilot deployment

- VMM = VMware Workstation 4.5
- dist. storage = user-level chunk store
- major vulpes changes
- 23 users, peak usage Jan-Aug 2005
- extensive analysis of usage data
- predicted high value of CAS
- revealed fatal flaw in client design

ISR → “Virtual Desktop Infrastructure (VDI)”

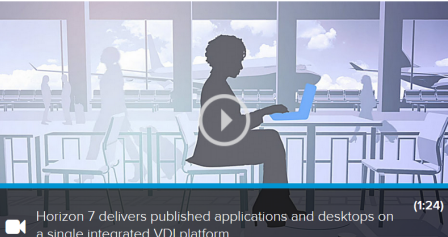
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VMware Horizon 7 is the leading platform for virtual desktops and applications.
Provide end users access to all of their virtual desktops, applications, and online services through a single digital workspace.



What's New in Horizon 7
Discover the newest capabilities in Horizon, including JMP, faster application access, and a better user experience for Skype for Business.
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A Better Experience for Skype for Business
VMware has partnered with Microsoft to deliver an optimized solution for Skype for Business.
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Horizon 7 delivers published applications and desktops on a single integrated VDI platform. (1:24)

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Easy Virtual Desktop Infrastructure (VDI)


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There is an easier way to implement VDI

Plan, deploy and run your desktop virtualization environment more simply. Dell easy VDI solutions meet your needs so you can be more efficient, responsive and competitive.

- Reduce the time required to configure and deploy VDI from weeks to hours and scale efficiently when the time is right.
- Lower your cost per user with HCI solution that's right-sized for your organization.
- Relieve IT of time-consuming tasks (planning, installation, operation and management) and empower them to focus on more strategic projects.
- Improve security from the data center to the cloud.

Wise Datacenter solutions accommodate specific use cases and satisfy various diverse requirements.



Components

Whether you want to do it yourself or purchase cloud client-computing "as-a-service," Dell solutions make VDI easier than ever. Choose from our wide range of simple, manageable and reliable VDI solutions, leveraging re-defined storage (SDS) technologies in hyper-converged infrastructures.

Easy Virtual Desktop Infrastructure (VDI)
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Deliver on the promise of virtual desktop infrastructure



IntelliFlash Arrays make it amazingly economical to scale your virtual desktops from pilot to production.

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Citrix XenApp and XenDesktop vs. VMware Horizon

XenApp and XenDesktop lead the industry in desktop and app virtualization, delivering the only complete solution mobilizing Windows® apps and desktops for any use case. VMware Horizon View's inadequate solution and lowest common denominator approach to computing impairs the user experience, causes headaches for IT, and fails to meet key business requirements by delivering only basic capabilities to customers.

Customers share why they choose Citrix—the only proven solution for virtualizing Microsoft Skype for Business.

Read the report >>

Discarding Legacy is Expensive

Disrupts existing business workflows

Requires re-training of employees

Requires new troubleshooting skills and best practices

Hidden costs greatly outweigh visible savings

IBM Mainframes

https://www.ibm.com/support/knowledgecenter/en/linuxonibm/liaag/wkvm/wkvm_c_overview.htm

The screenshot shows the IBM Knowledge Center interface. At the top, the IBM logo and 'IBM Knowledge Center' are visible. The breadcrumb trail reads: Home > Linux on IBM Systems > Linux on Z and LinuxONE > Performance > Performance > Linux on KVM > KVM Network Performance - Best Practices and Tuning Recommendations >. The main heading is 'Overview'. A search bar is present with the text 'Search in this product...'. Below the heading, there is a 'Table of Contents' section with a 'Change product' link. The table of contents lists several articles, with the current article, 'KVM Network Performance - Best Practices and Tuning Recommendations', highlighted. The main content area contains two paragraphs. The first paragraph states: 'The IBM Z platforms are the latest generation in the IBM® family of mainframe offerings. The IBM mainframes have a long legacy from being first produced over 50 years ago. The system technology has continued to expand and evolve enabling the IBM mainframe releases to continue to offer capabilities and features enterprise customers require.' The second paragraph states: 'The IBM Z family maintains full backward compatibility. This means that current systems are the direct, lineal descendants of System/360 announced in 1964, and System/370 from the 1970s. Many applications written for these systems can still run unmodified on the newest IBM Z system over five decades later!'¹ A red arrow points from the text '50 years of upward compatibility' below to the underlined sentence in the second paragraph. A 'Rate this content' button is visible on the right side of the page.

50 years of upward compatibility

IBM earnings: z16 mainframe 'outperforming' previous generations

Things are looking up for Big Blue as revenue beats expectations

July 25, 2024 By: Matthew Gooding [Have your say](#)



<https://www.datacenterdynamics.com/en/news/ibm-earnings-z16-mainframe-outperforming-previous-generations/>

IBM's CFO said its z16 mainframe is outperforming previous generations of the system as the company posted quarterly financial results ahead of market expectations.

Big Blue's results for the three months to the end of June 2024 showed it brought \$15.77 billion in revenue, up 1.9 percent year-on-year and more than the \$15.62 billion predicted by analysts.

Its infrastructure segment, which includes mainframe computers, as well as hybrid cloud and other distributed infrastructure, reported \$3.65 billion in revenue, up 0.8 percent and ahead of the expected \$3.51 billion.

Speaking on the company's latest earnings, IBM CFO Jim Kavanaugh said the business has been buoyed by demand for the z16, which launched in [2022](#).



How Big is the Windows Legacy World?

<https://blogs.windows.com/windowsexperience/2015/04/29/welcoming-developers-to-windows-10/>

Microsoft | Windows Blogs Windows 10 Devices Windows Developer Microsoft Edge Microsoft 365

All Microsoft

Windows Insider Program Windows 10 Tips Mixed Reality



2015 **16 million**

APRIL 29, 2015 11:31 AM

Welcoming Developers to Windows 10

By [Terry Myerson](#) / Executive Vice President, Windows and Devices Group



Win32 applications. We look forward to more of the current 16 million Win32 applications growing their distribution through the Windows Store.

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Celebrating a new decade of Windows devices and innovation at CES 2020

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Microsoft

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2018

35 million

NOVEMBER 13, 2018 10:00 AM

Windows 10 Quality approach for a complex ecosystem

By [Mike Fortin](#) / Corporate Vice President, Windows

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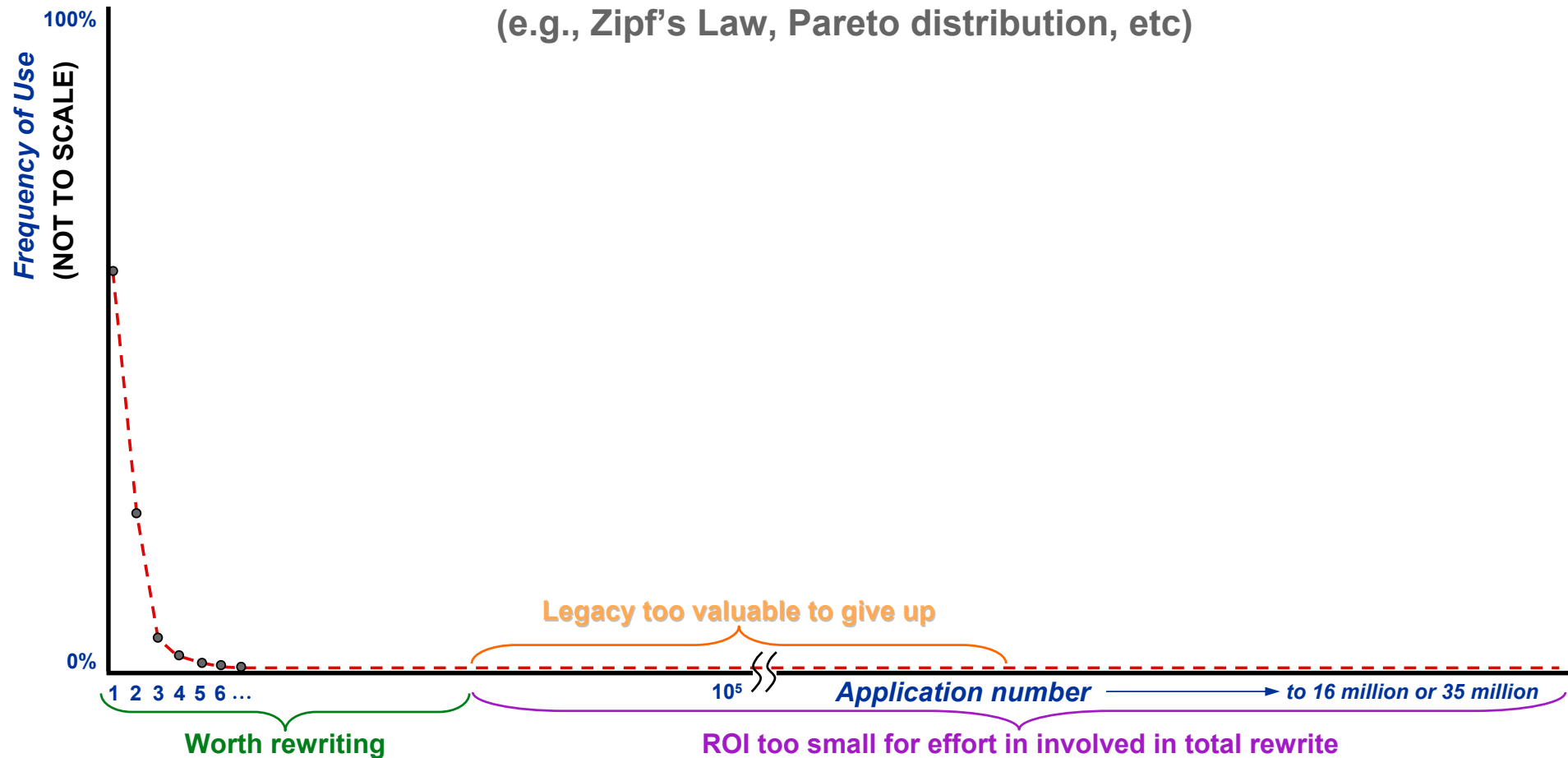
hundreds of millions of customers. With Windows 10 alone we work to deliver quality to over 700 million monthly active Windows 10 devices, over 35 million application titles with greater than 175 million application versions, and 16 million unique hardware/driver combinations. In addition,

RE



Usage Highly-skewed and Very Long-tailed

(e.g., Zipf's Law, Pareto distribution, etc)



Virtual Machines

Key to Supporting Legacy Software

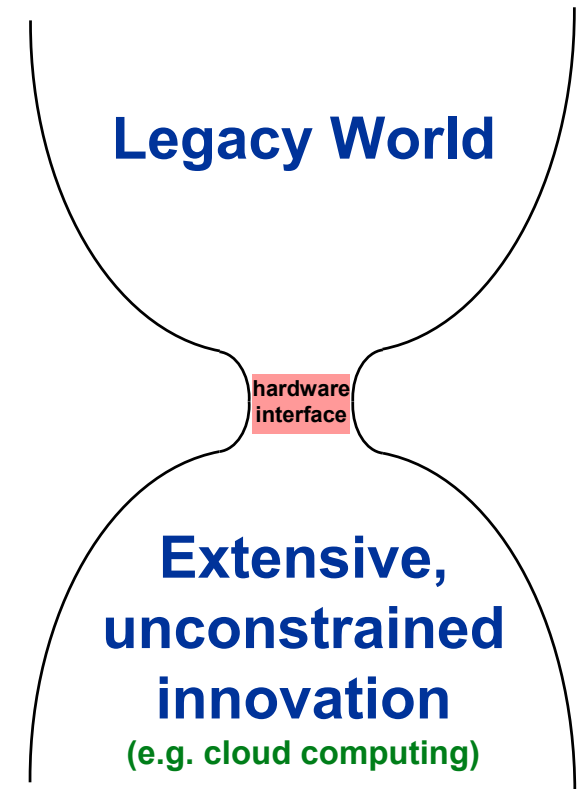
VMs are the “secret sauce” for legacy challenges

Over ~50 years, VM-based solutions have relieved pain while

- 1. pain points in computing have shifted*
- 2. legacy investments are preserved*
- 3. systems remain robust, stable, easy to deploy*

Note that

- **exact form of legacy investment may vary**
application software, system software, enterprise workflows, user learning/culture, ...
- **focus on hardware virtualization (of near-perfect fidelity)**
not para-virtualization, not language VMs (e.g. JVM)



Virtual Desktop Infrastructure (VDI)

On-demand access to a VM instance that represents your desktop

Many commercial implementations

e.g. VMware Horizon, Citrix XenDesktop, Microsoft Windows VDI, ...

RDP requires LAN bandwidth and latency to user

- many attempts to loosen these bounds by clever protocol optimizations
- only work up to a point, inherently fragile
- hence VDI deployments typically constrained to enterprise campuses

What is Missing with VDI Today?

Wide-area user mobility on the Internet

“Anywhere, anytime” access today means “Web access”

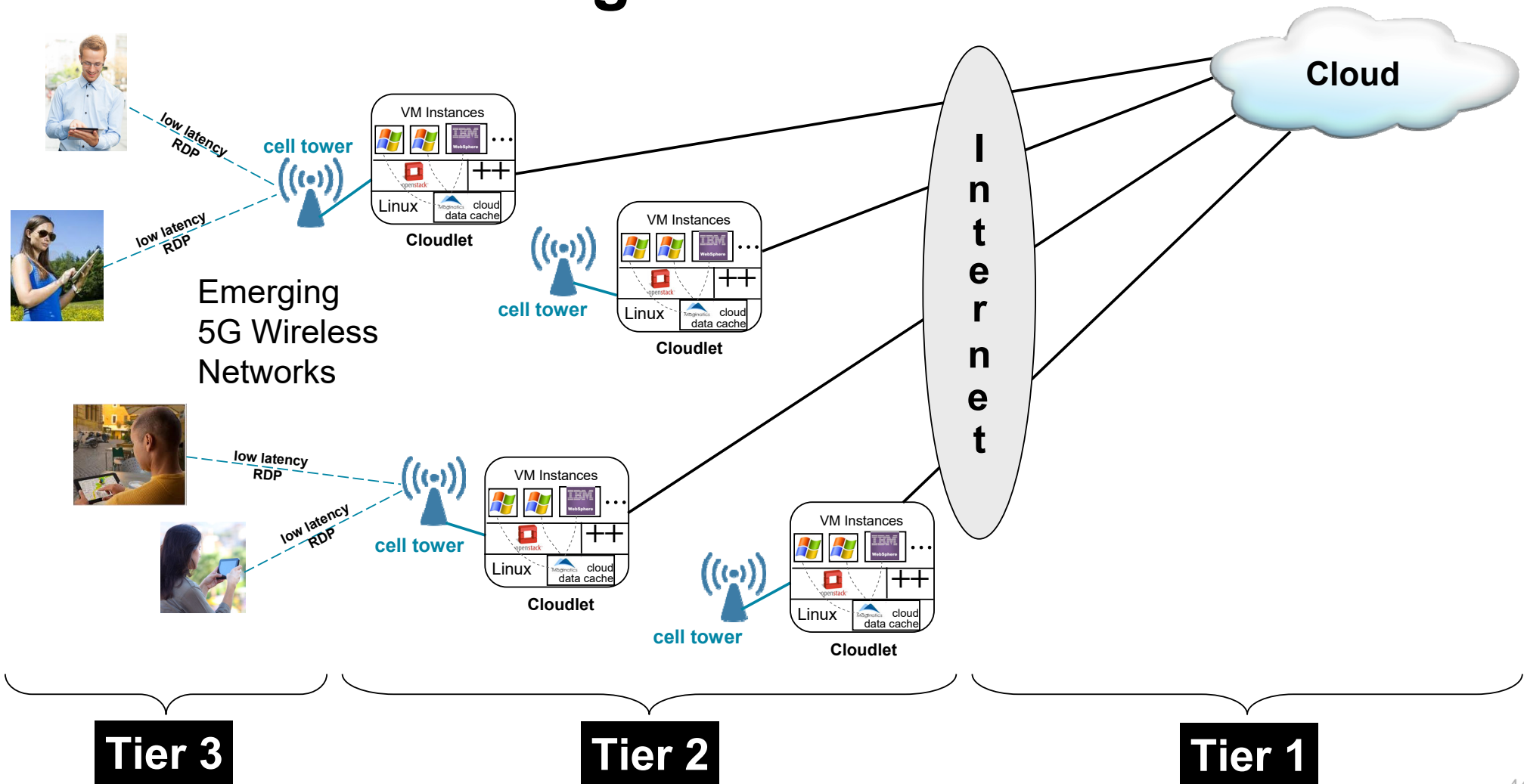
- “Web programming” explicitly recodes applications (e.g. Office 365)
- essential to tolerate the latency and bandwidth limits of the Internet

How can “anywhere, anytime” apply to access to your desktop VM?

Solution: *deliver your desktop VM to cloudlet closest to you*

By construction, the “last-mile network” has the LAN attributes needed for RDP

EdgeVDI Vision



Delivering Your Desktop Anywhere, Anytime

How do we do it?

Approach 1: send VM image to optimal cloudlet, then launch VM instance

- **Problem: long initial delay before launch; VMs are big, bandwidth is poor**
streaming implementations can work, but still suboptimal

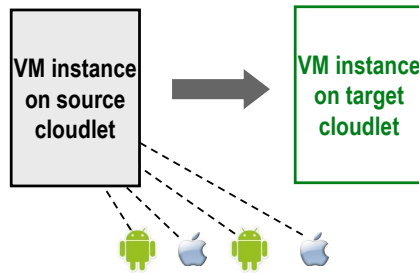
Approach 2: launch VM image at current cloudlet, interact remotely

- **Problem: quick launch but horrible interactions**
(long latency, poor bandwidth)

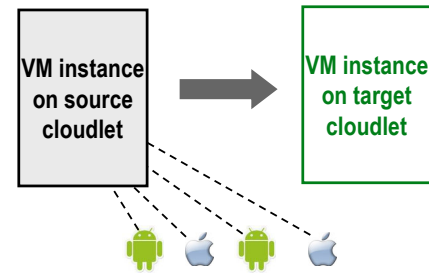
Approach 3: *combine first two approaches*

- launch VM instance at current cloudlet and start interacting
- while interacting, migrate VM instance to nearest cloudlet
- when fully migrated, switch to get LAN-quality interactions
switch time is referred to as “down time”
- essence of *live migration* (Clark et al 2005), aka “vMotion” (VMware product)

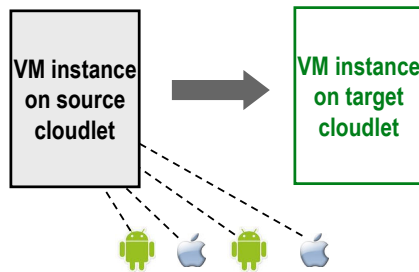
How Live Migration Works



Step 1: Copy VM's memory and disk state while source continuing to service associated clients



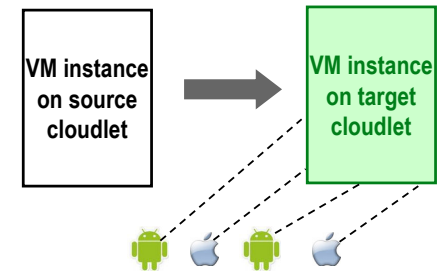
Step 2: Identify state changes because of VM execution during Step 1. Copy those changes.



Step 3: Identify state changes because of VM execution during Step 2 (often smaller). Copy those changes.

Step 4, Step 5, Step 6 . . .

repeat until dirty state is below some threshold; then pause for "down time", make one last copy and then flip



Step N: Flip control, resume and redirect (redirection may or may not be transparent to clients, depending on VLAN use)

Challenge: Live Migration at 5-25 Mbps

(3-4 orders of magnitude lower than typical data center LAN speed of 10-40 Gbps)

Our implementation is called **VM Handoff** (Kiryong Ha: 2017 PhD thesis)

- aggressive use of **deduplication** and **bandwidth-adaptive compression**
- optimizes for **total handoff time**, not for shortest down time

Open source implementation on Linux for KVM/QEMU

Driving principles of implementation

- **Every non-transfer is a win.**
Use deduplication, compression and delta-encoding to ruthlessly eliminate avoidable transfers.
- **Keep the network busy.**
Network bandwidth is a precious resource, and should kept at the highest possible level of utilization.
- **Go with the flow.**
Adapt at fine time granularity to network bandwidth and cloudlet compute resources.

In Closing

VMs have come to rescue many times in the past six decades

They look ready to be valuable once again (EdgeVDI)

Remember: *“Legacy is Tyranny”* (CD-ROM size, driving left/right, DVD format ...)

VMs enable innovation while preserving legacy