



# The Configurable Cloud -- *Accelerating Hyperscale Datacenter Services with FPGAs*

Andrew Putnam – Microsoft

# What is a Cloud / Big Data Application?



Microsoft  
Dynamics



yammer



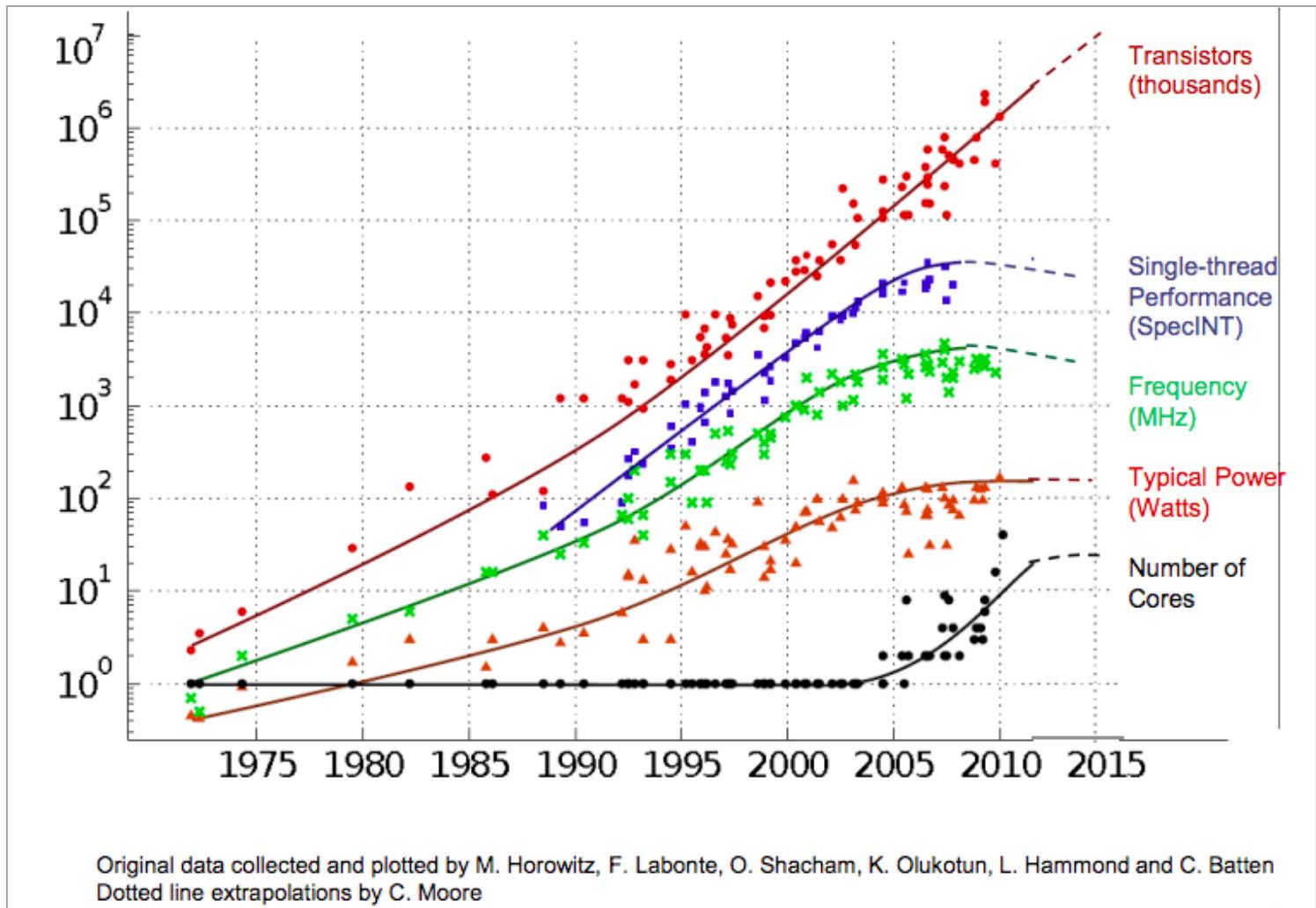
IaaS

PaaS

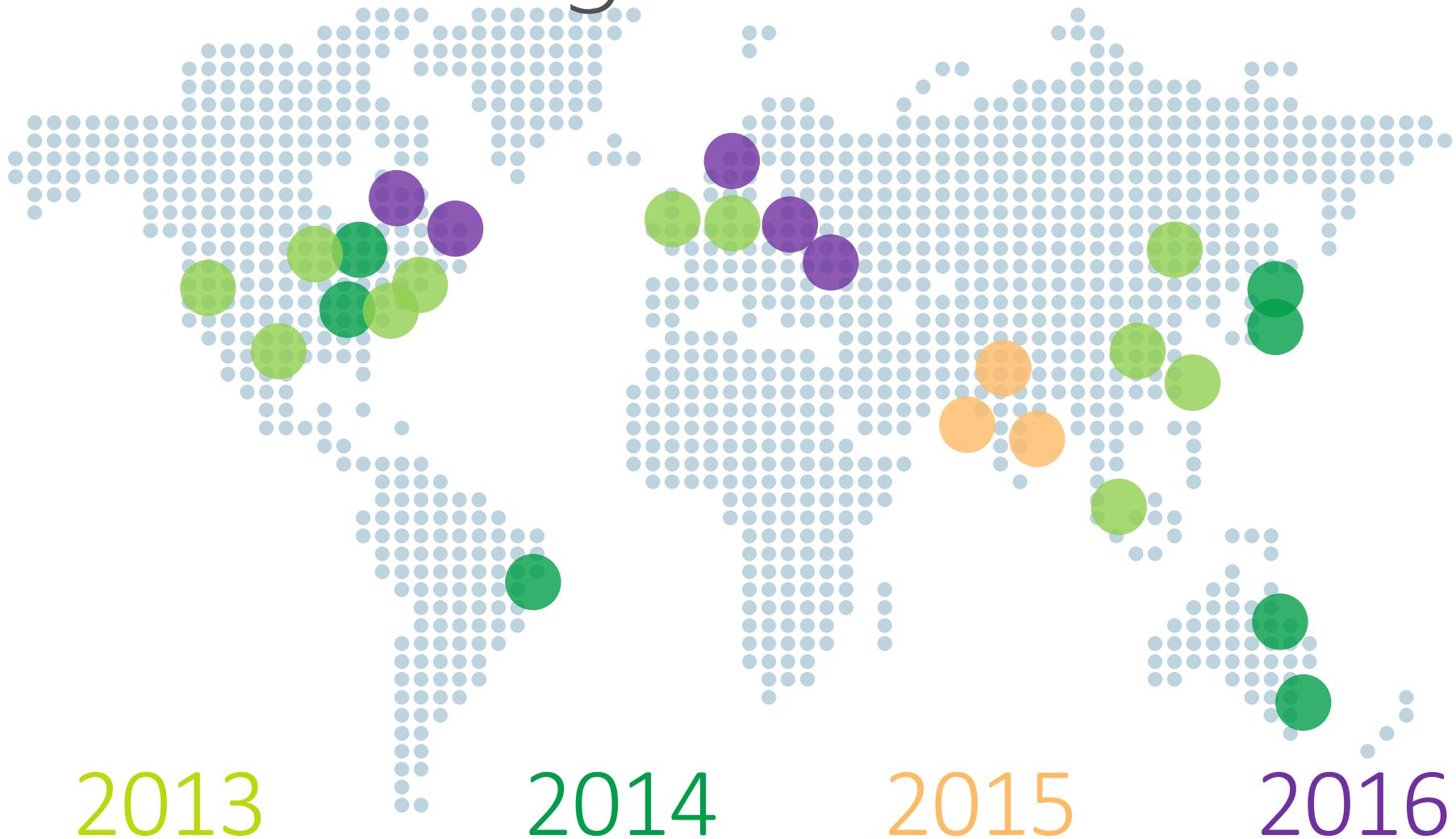
SaaS

# Technology Scaling

- Moore's Law (transistors) is still alive
- Dennard Scaling (keeping energy under control) is dead
- 2x users requires 83% more servers
- Need increased efficiency



# Datacenter Scaling



~100%+ Growth for the past 4 years

# Modern HyperScale Datacenters

- Microsoft > 1,000,000 servers
- 100s of MegaWatts
- \$100M+ power bill



## TOP 10 Sites for November 2016

For more information about the sites and systems in the list, click on the links or view the complete list.

Rank	Site	System	Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	National Supercomputing Center in Wuxi China	<b>Sunway TaihuLight</b> - Sunway MPP, Sunway SW26010 260C 1.45GHz, Sunway NRCPC	10,649,600	93,014.6	125,435.9	15,371
2	National Super Computer Center in Guangzhou China	<b>Tianhe-2</b> ( <b>MilkyWay-2</b> ) - TH-IVB-FEP Cluster, Intel Xeon E5-2692 12C 2.200GHz, TH Express-2, Intel Xeon Phi 31S1P NUDT	3,120,000	33,862.7	54,902.4	17,808
3	DOE/SC/Oak Ridge National Laboratory United States	<b>Titan</b> - Cray XK7 , Opteron 6274 16C 2.200GHz, Cray Gemini interconnect, NVIDIA K20x Cray Inc.	560,640	17,590.0	27,112.5	8,209
4	DOE/NNSA/LLNL United States	<b>Sequoia</b> - BlueGene/Q, Power BQC 16C 1.60 GHz, Custom IBM	1,572,864	17,173.2	20,132.7	7,890

### Datacenter:

**~100,000 dual-socket servers**

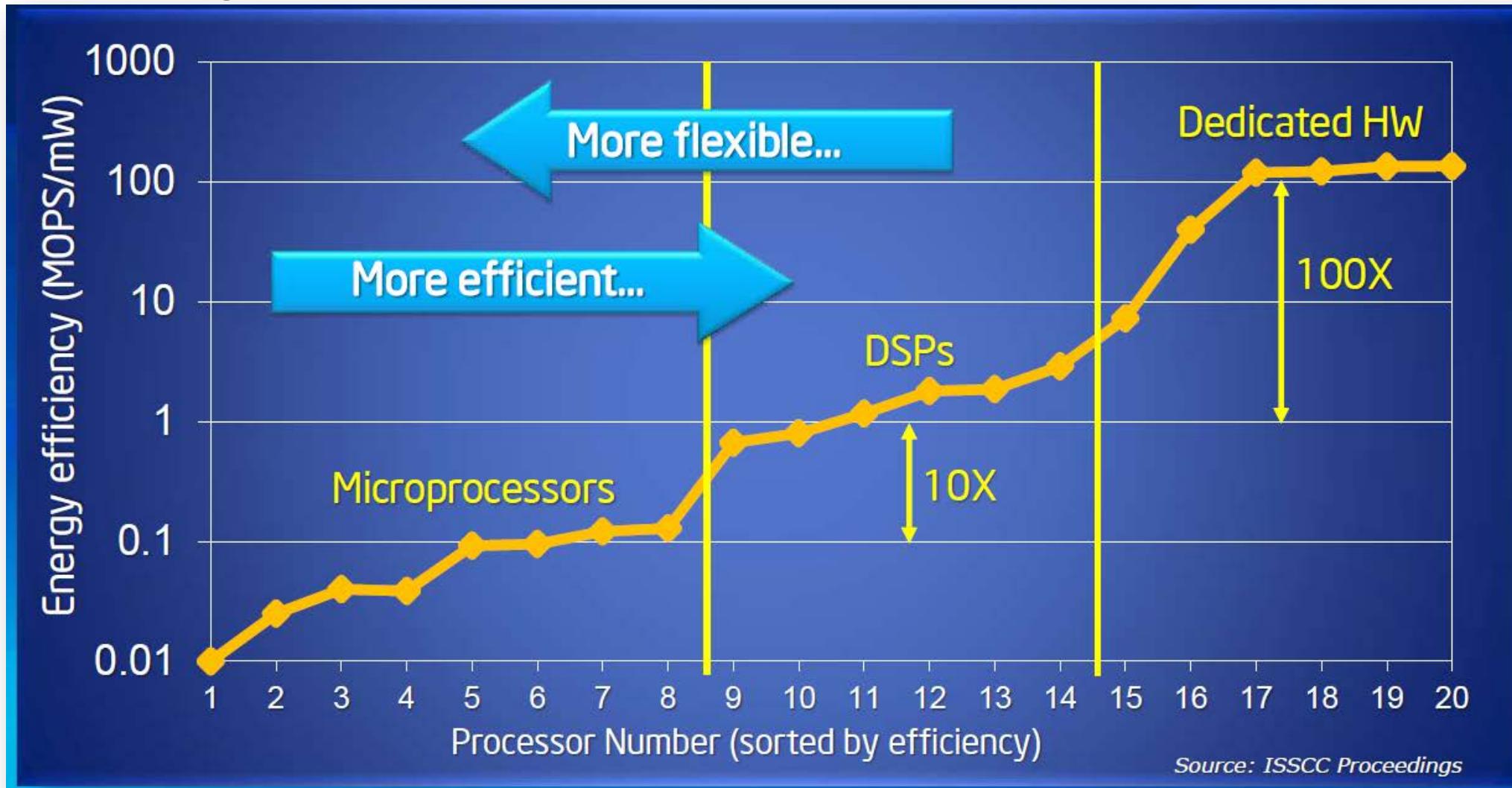
40,960 single-socket servers

16,000 dual-socket servers  
3 Xeon Phi / server

18,688 single-socket servers  
1 Tesla GPU / server

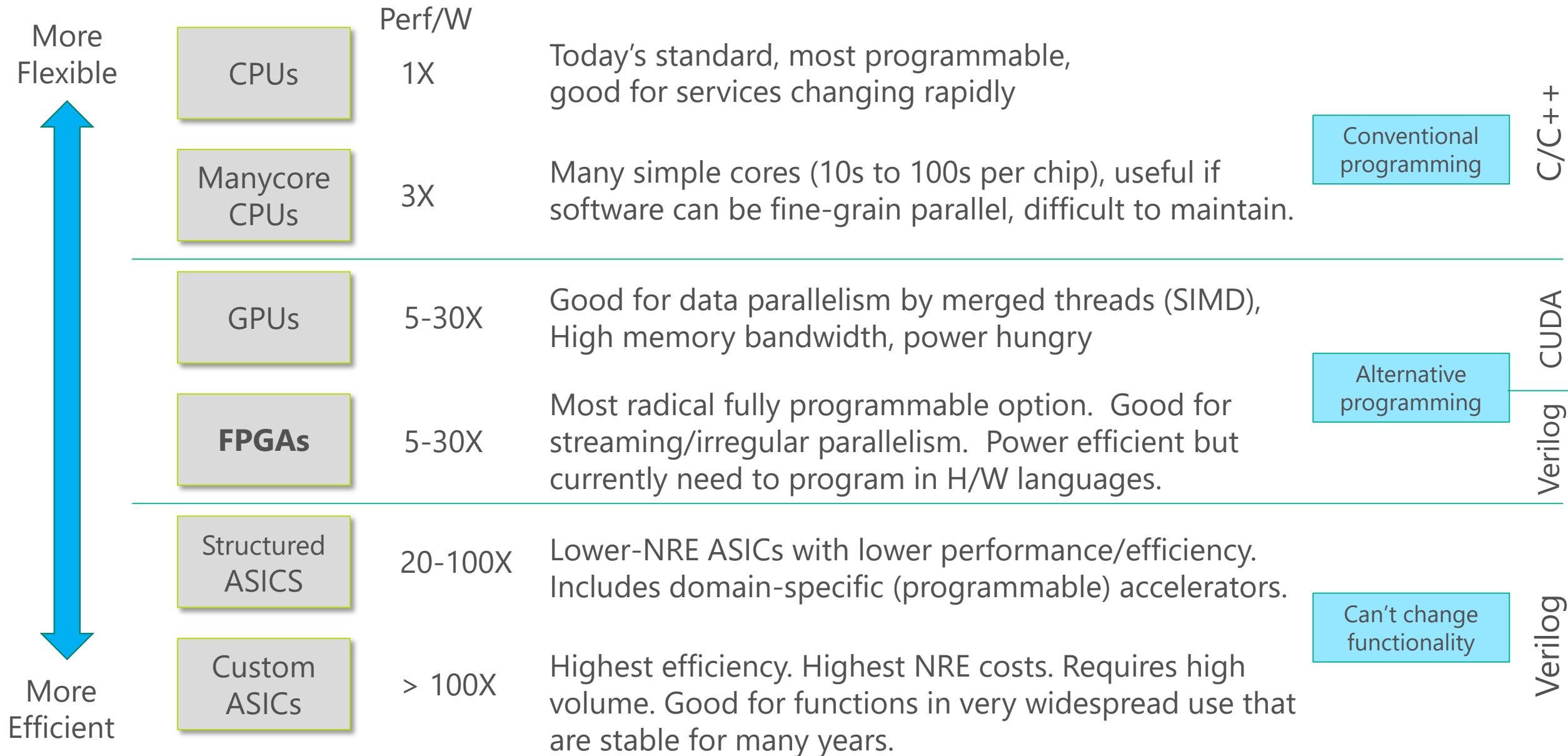
98,304 single-socket servers

# Efficiency via Specialization



Source: Bob Broderson, Berkeley Wireless group

# Silicon Technologies for Computing

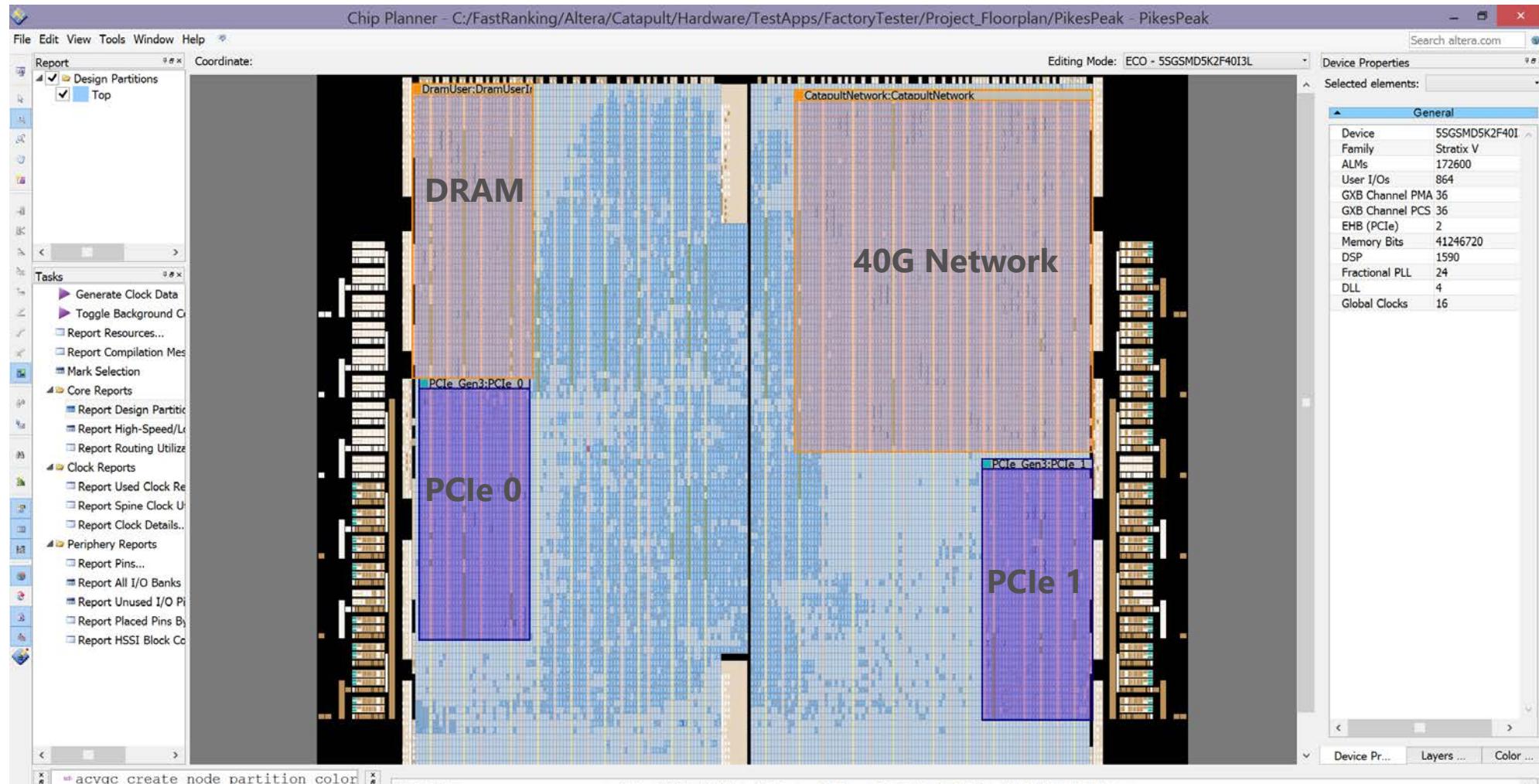


# What are FPGAs?

- Field Programmable Gate Array
- FPGAs are a sea of generic logic and interconnect
  - “Silicon Legos” – build them into exactly the right circuit for each task
- Special-purpose hardware (FPGAs) is faster and more efficient than general-purpose hardware (CPUs)
- **Change the hardware anytime!**
  - 100 ms to 1 second reconfiguration time

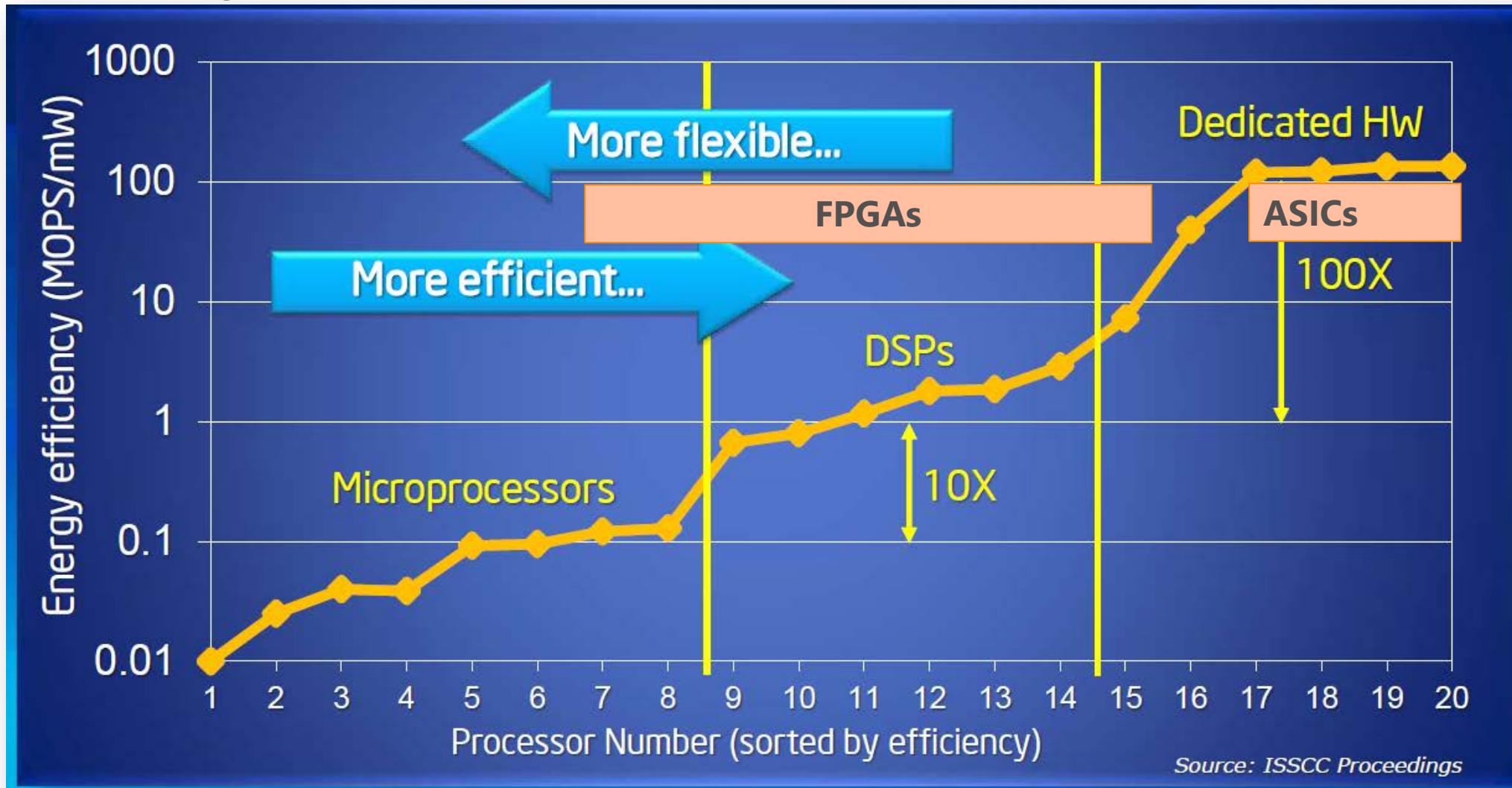


# FPGA Physical Layout



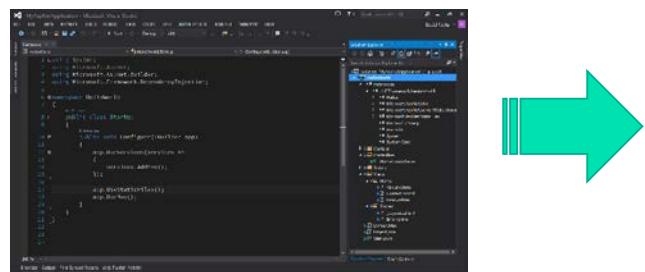
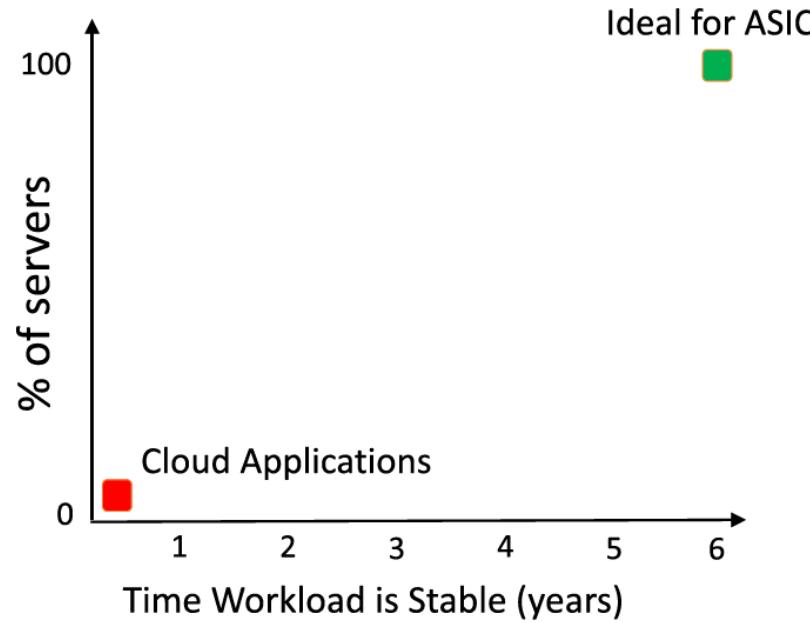
Customize both the processing logic *and* the I/O

# Efficiency via Specialization



Source: Bob Broderson, Berkeley Wireless group

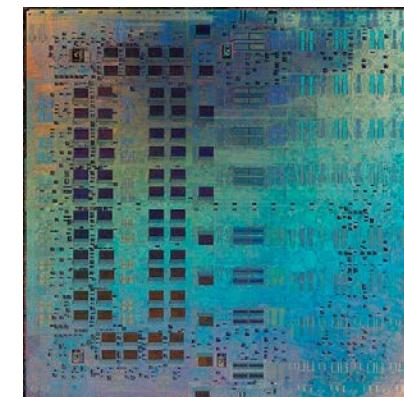
# Why not use ASICs?



Software



FPGA



ASIC

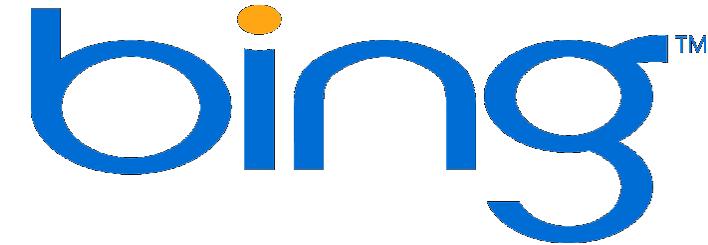
# Why not use GPUs?

- SIMD is best for batch jobs
- Customer-facing (interactive) workloads are small batches, need low latency
- Limited floating point for most workloads
  - Scientific computing and ML are exceptions
- *Optimize for the whole fleet, not for one application*



EnterPrise-XR-P

Also.... power

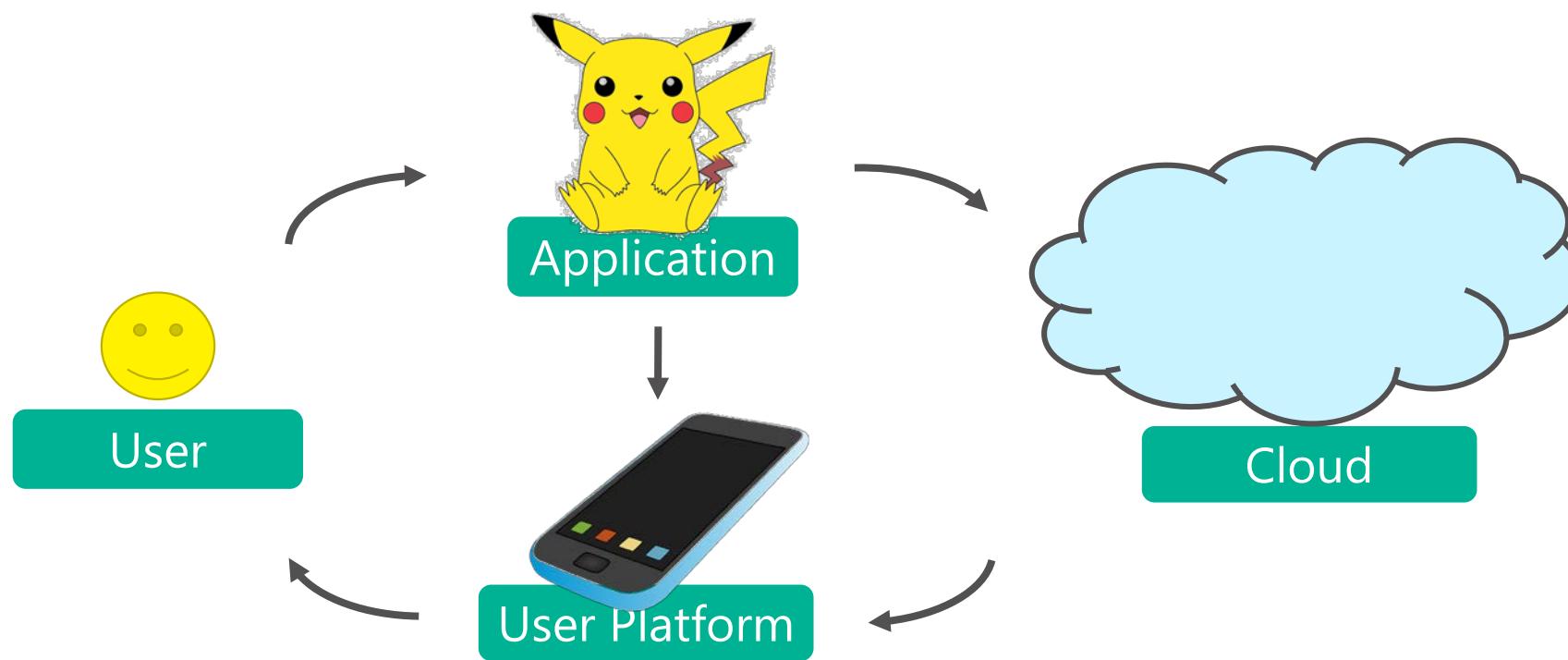


# Bing: How it all Began

- Launched June 1, 2009
  - MSN Search
  - Windows Live Search
  - Live Search
- October 2010: Approached Microsoft Research for help optimizing performance
- December 2010: Designed an FPGA accelerator for one critical stage
  - First designed at Starbucks – in PowerPoint

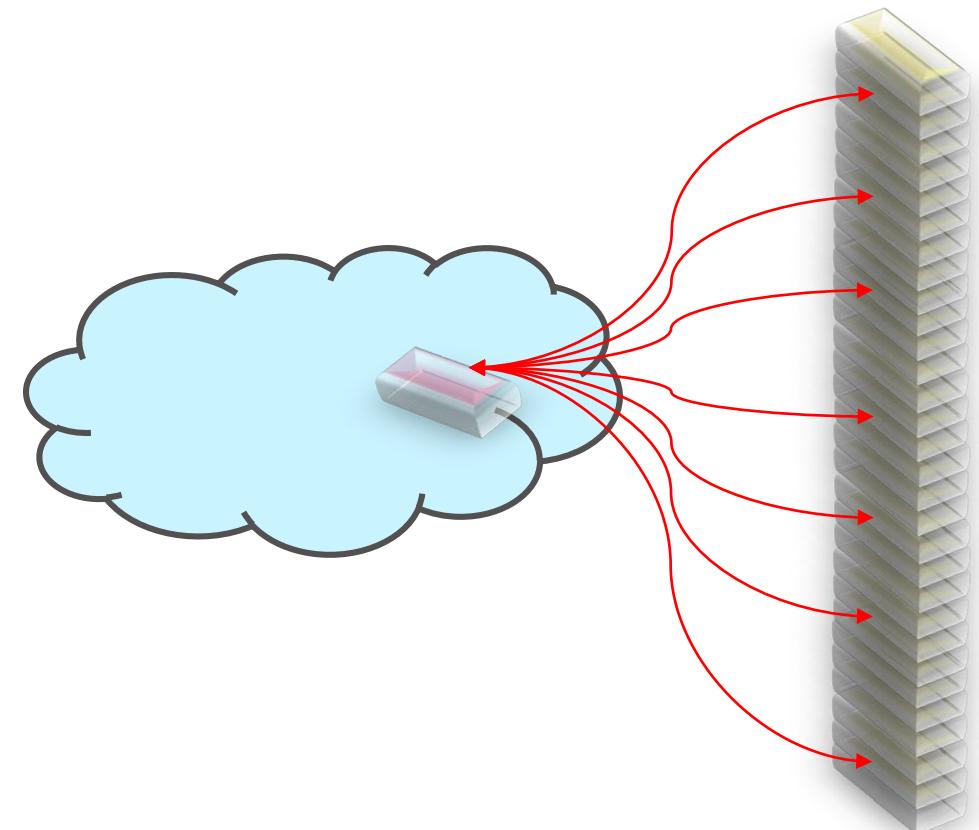
# User Demands

- Cloud users want interactive applications
- User platforms cannot do all the processing
- Users want look/feel/predictability of local processing



# 99%+ Responsive

- Cloud services are typically thousands of servers working together
- Overall response time is determined by slowest node
- 1% of nodes can make all the others look bad

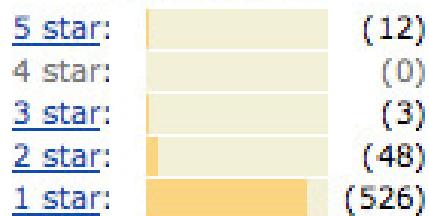


# 99%+ Reliable

- When the Cloud is unavailable, apps stop working
- No backup – Clients can't run all functionality
- Goal of 99.999% availability is typical
- Redundancy helps, but adds to cost and complexity

## Customer Reviews

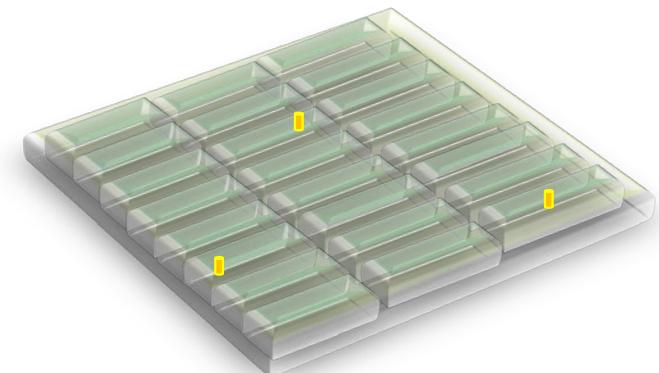
589 Reviews



### Average Customer Review

(589 customer reviews)

"Service disruptions are temporary. 1-star reviews are forever."

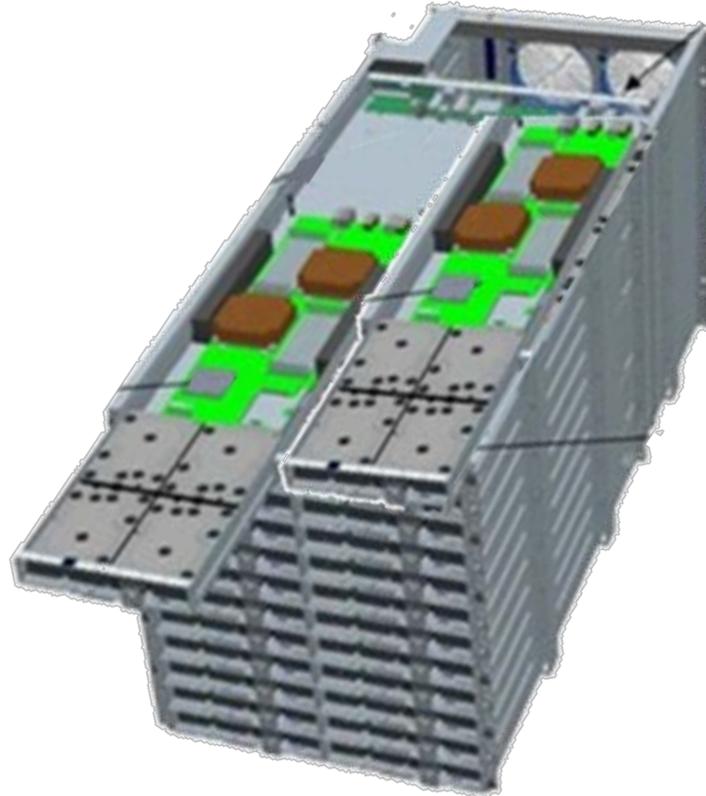


# Datacenter Environment

- Machines last 3-5 years, purchased ~quarterly
- Machines usually repurposed multiple times
- Little/no HW maintenance, no accessibility
- Most datacenter problems are caused by misconfigurations and missed test coverage
- Load balancing, rapid scale up/down are key
- Homogeneity is highly desirable

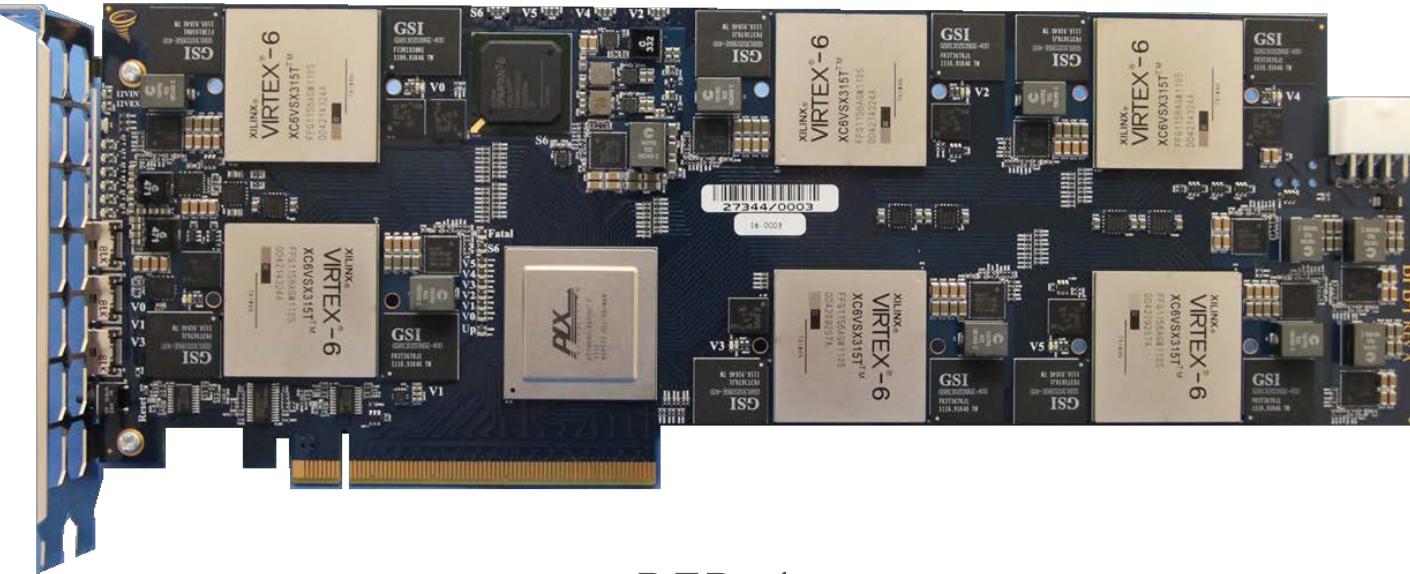
# Datacenter Servers

- Microsoft Open Compute Server
- 1U,  $\frac{1}{2}$  wide servers
- Enough space & power for  $\frac{1}{2}$  height,  $\frac{1}{2}$  length PCIe card
- Squeeze in a single small ~25W card



# BFB-1

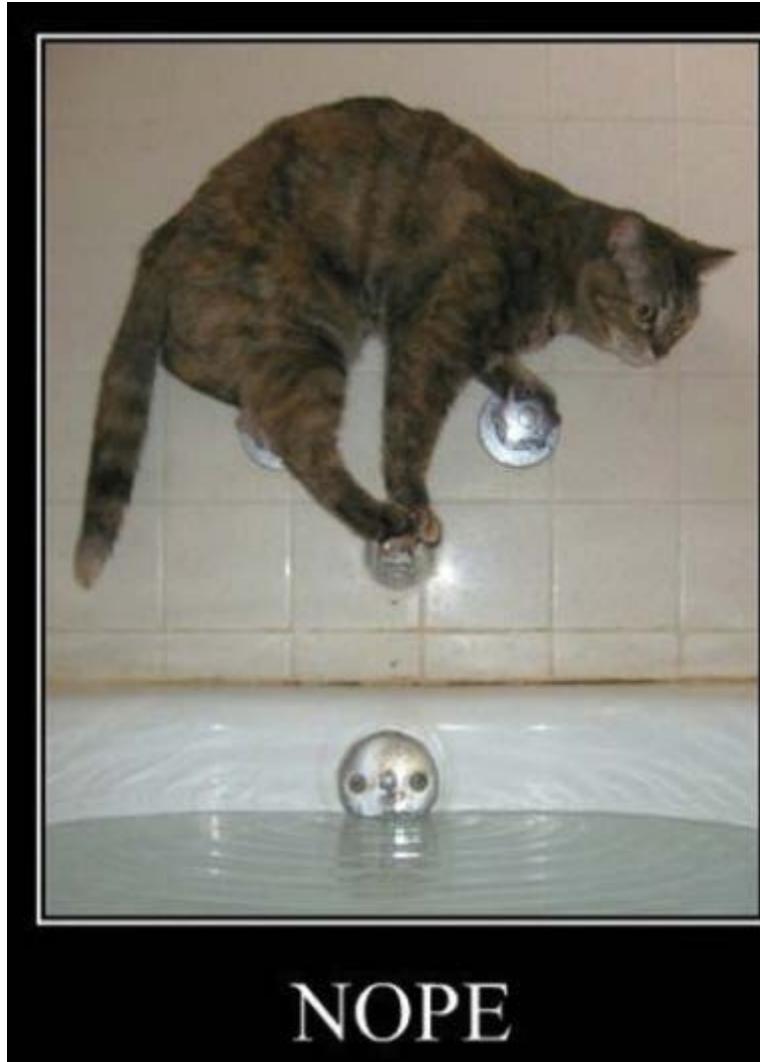
- Created a custom board with 6 big FPGAs
  - First designed at Starbucks (& Duke's Chowder House) – in PowerPoint



BFB-1

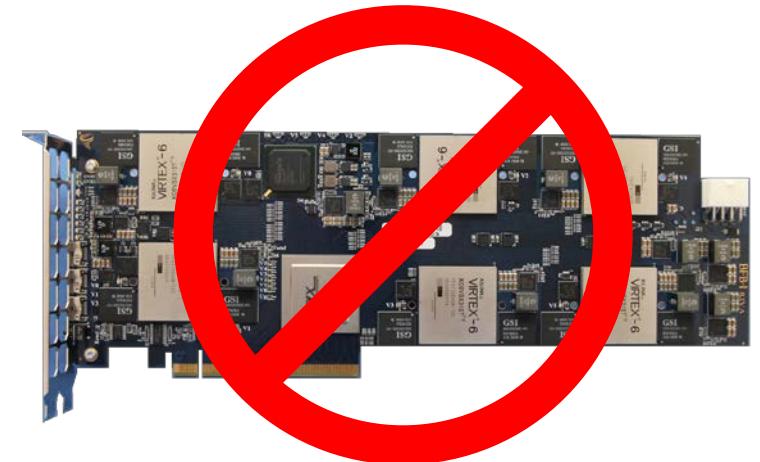


# And Datacenter Operations says...



# Centralized Model Complicates Deployment

- Single point of failure
- Server is different from the surrounding servers
- Complicates rack design, thermals, maintainability
- CPU network needed for FPGA communication
  - Definition of the Network In-cast problem
  - Precludes many latency-sensitive workloads
- Limited elasticity
  - What if you need more than six FPGAs?



# Fitting FPGAs in the Datacenter

- All servers should be the same
- How about just 1 FPGA in each server?
- Area must be small. Temperatures high. Power low.

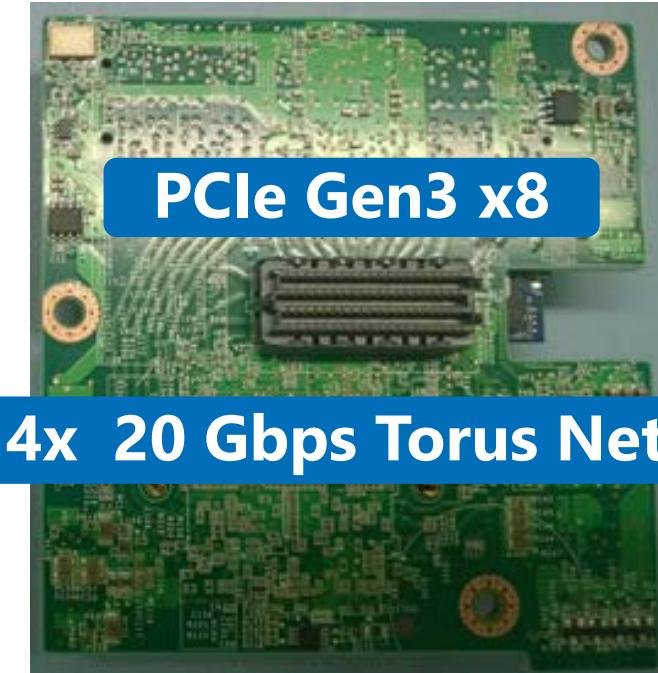


# Catapult v1 FPGA Accelerator Card

- Altera Stratix V GS D5
  - 172k ALMs, 2,014 M20Ks, 1,590 DSPs
- 8GB DDR3-1333
- 32 MB Configuration Flash



- PCIe Gen 3 x8
- 8 lanes to Mini-SAS SFF-8088 connectors
- Powered by PCIe slot

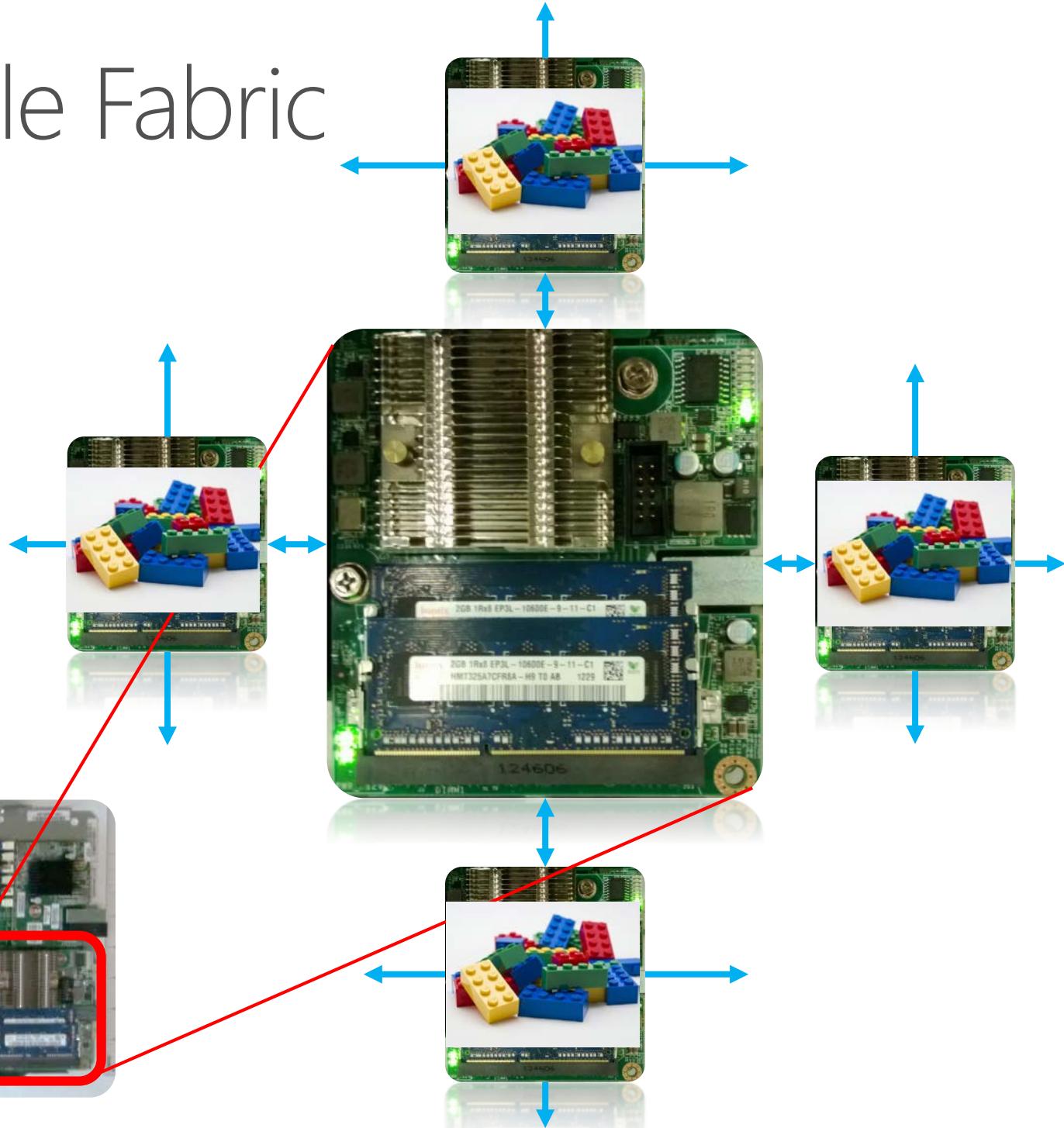


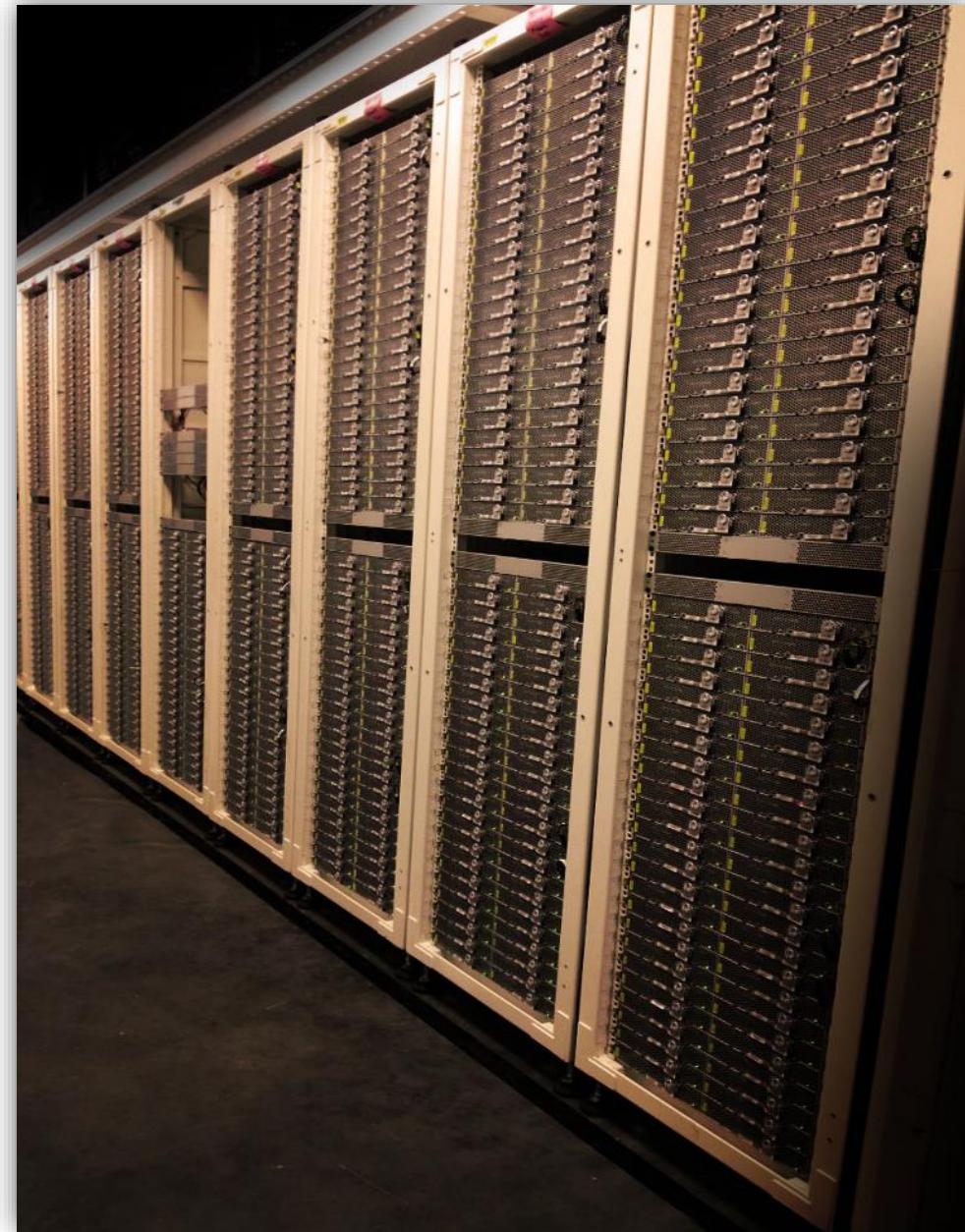
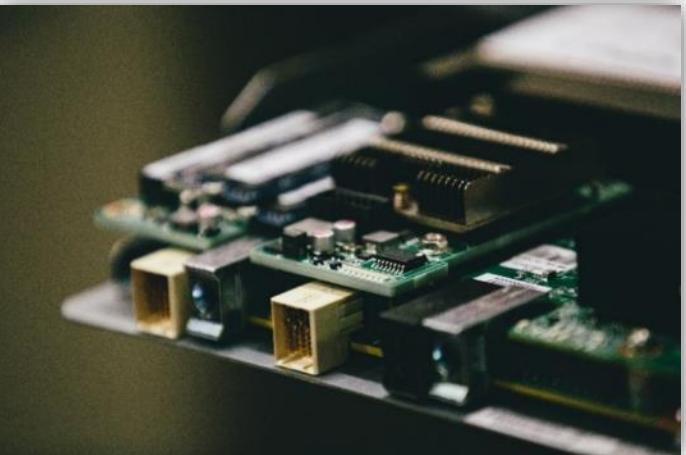
4x 20 Gbps Torus Network

# Scalable Reconfigurable Fabric

- 1 FPGA board per Server
- 48 Servers per  $\frac{1}{2}$  Rack
- Network among FPGAs:
  - 6x8 Torus at 20 Gb/link

Data Center Server (1U,  $\frac{1}{2}$  width)

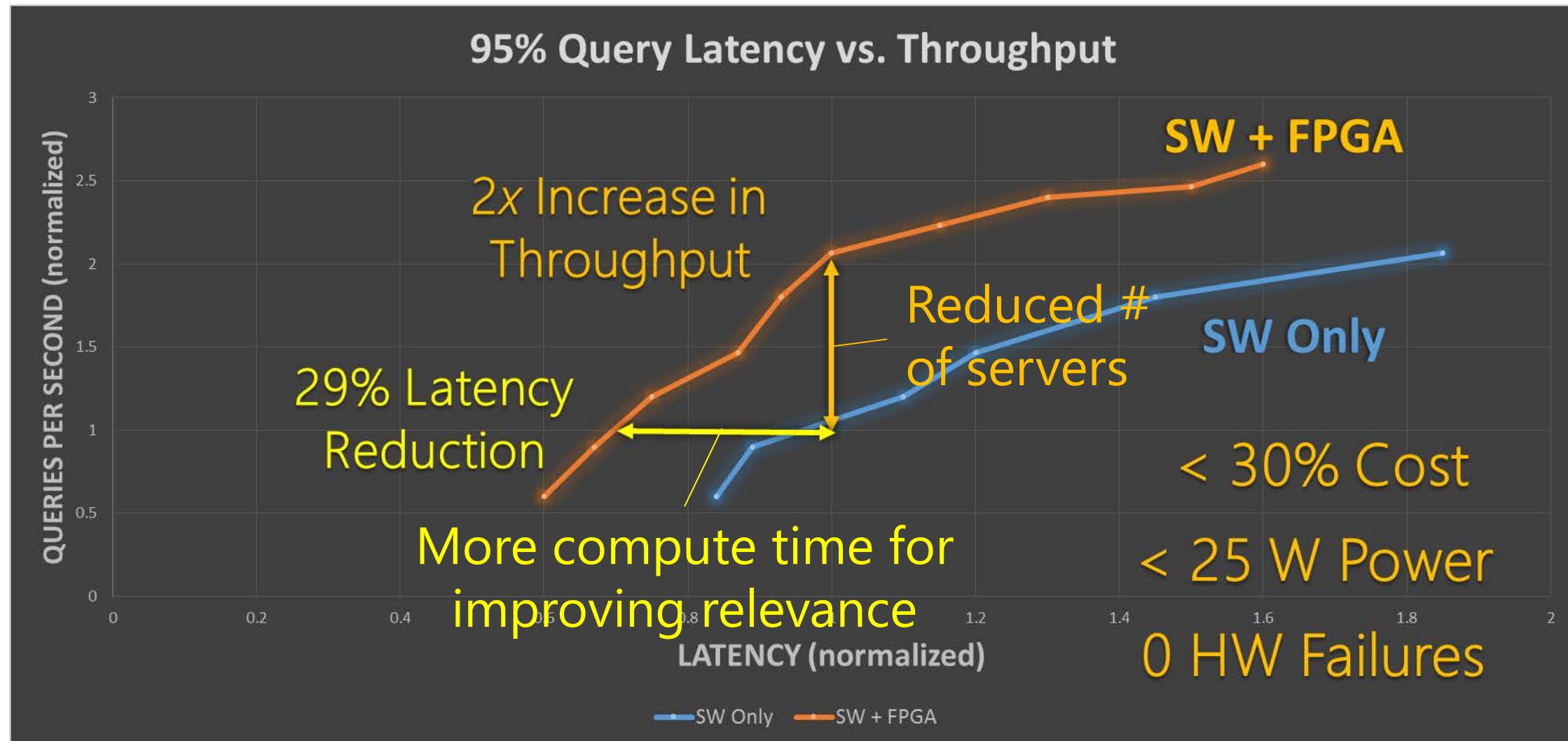




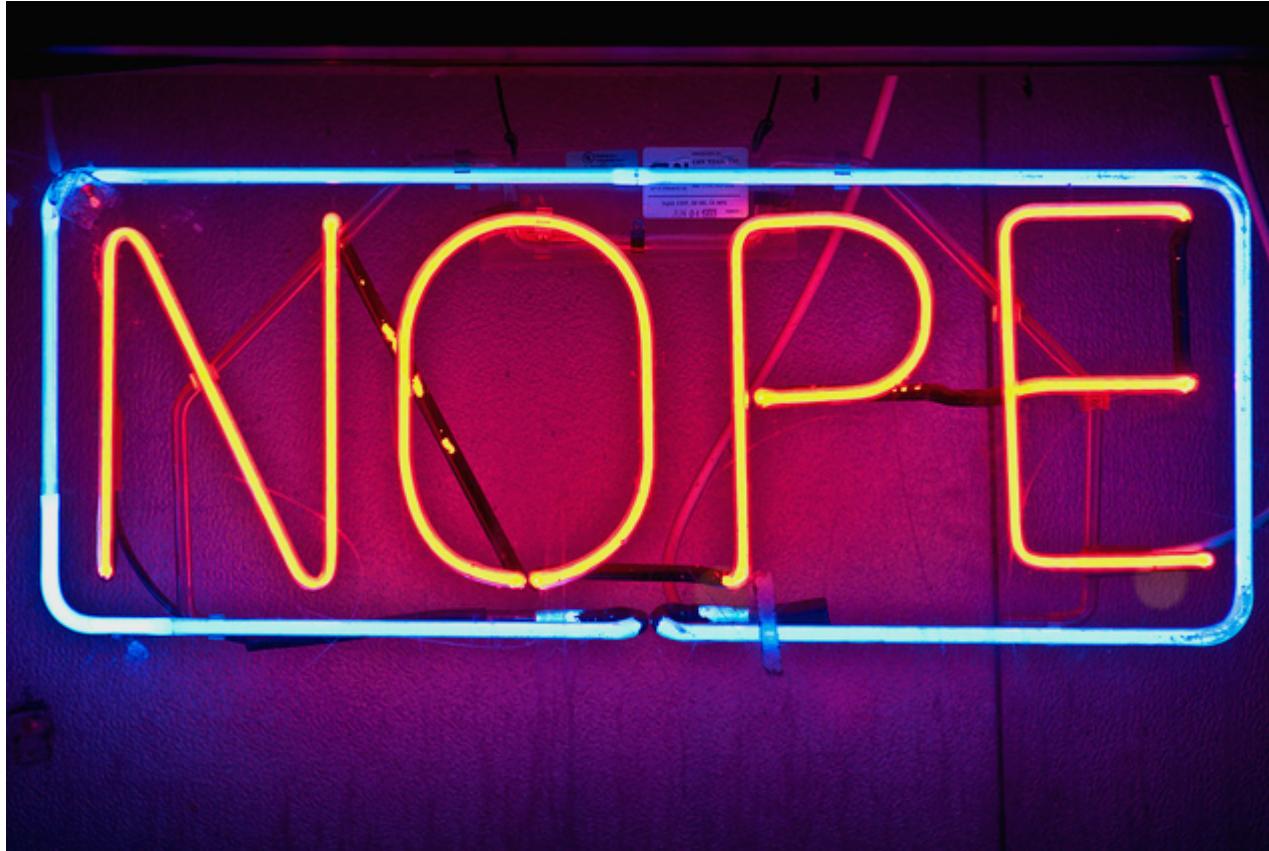
1,632 Server Pilot Deployed in a Production Datacenter

# Accelerating Large-Scale Services – Bing Search

1,632 Servers with FPGAs Running Bing Page Ranking Service (~30,000 lines of C++)



# Was Catapult v1 deployed into production?



5.8+ billion  
worldwide queries each month



250+ million  
active users



400+ million  
active accounts



2.4+ million  
emails per day

Microsoft®  
Exchange  
Hosted Services

8.6+ trillion  
objects in Microsoft Azure  
storage

Microsoft Azure



48+ million  
users in 41  
markets



50+ million  
active users



1 in 4  
enterprise customers



**50+** billion  
minutes of connections handled  
each month



# 200+ Cloud Services: Diversity

1+ billion customers · 20+ million businesses · 90+ markets worldwide

# Workload Diversity

- Bing was the big dog, but Azure grew much faster
- Compute offload for Bing isn't enough to justify hyperscale deployment
- Could go Bing-specific
  - Misconfiguration is the leading cause of problems in the datacenter
  - Increased hardware diversity means increased chances of misconfigurations
- Could try to do offload for all the other services
  - But is there enough time to learn each new application?

# Compute vs. Infrastructure

- *Compute* acceleration is application-specific

- Bing Ranking
- Machine Learning / DNNs



≈ 1-2 years



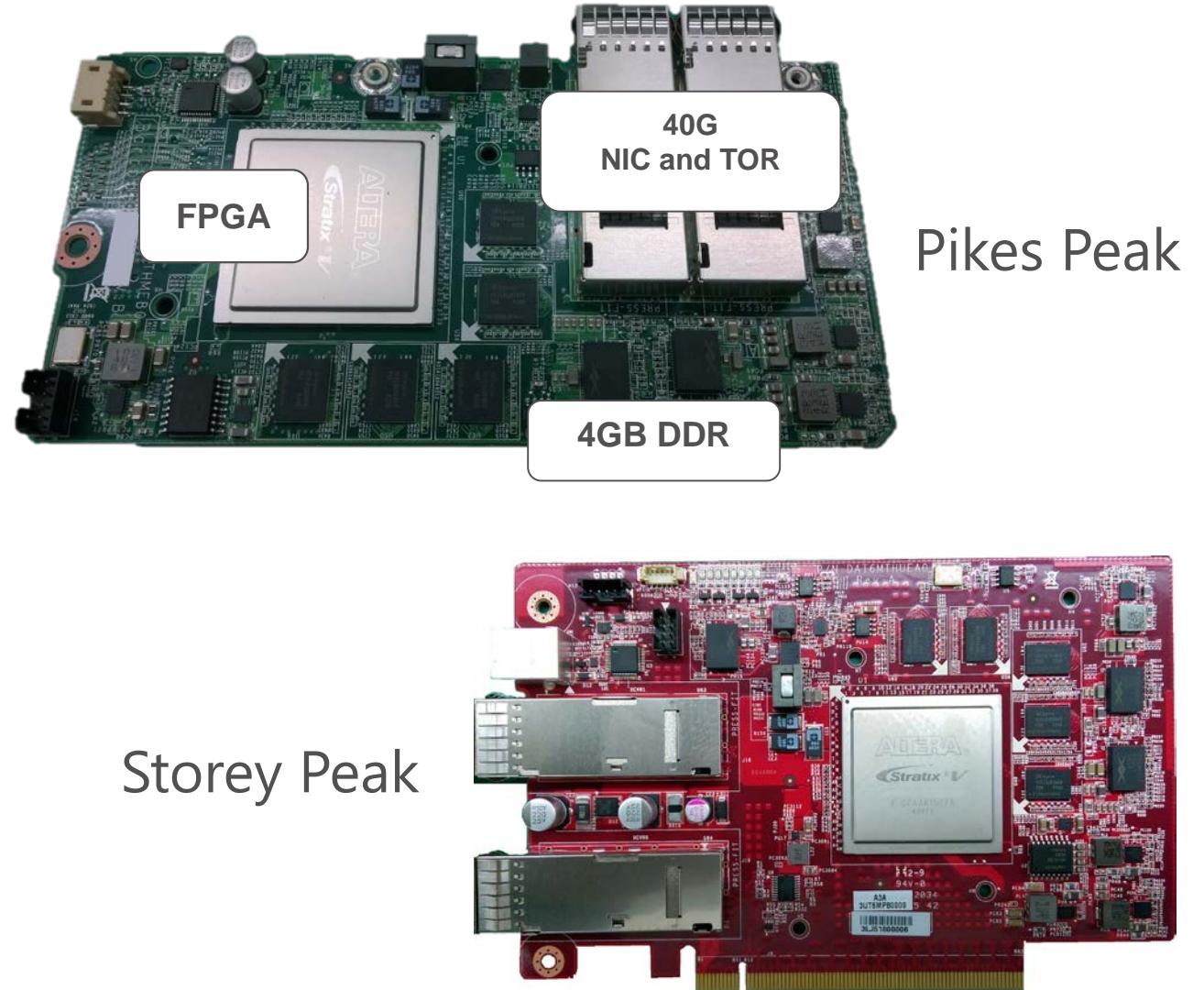
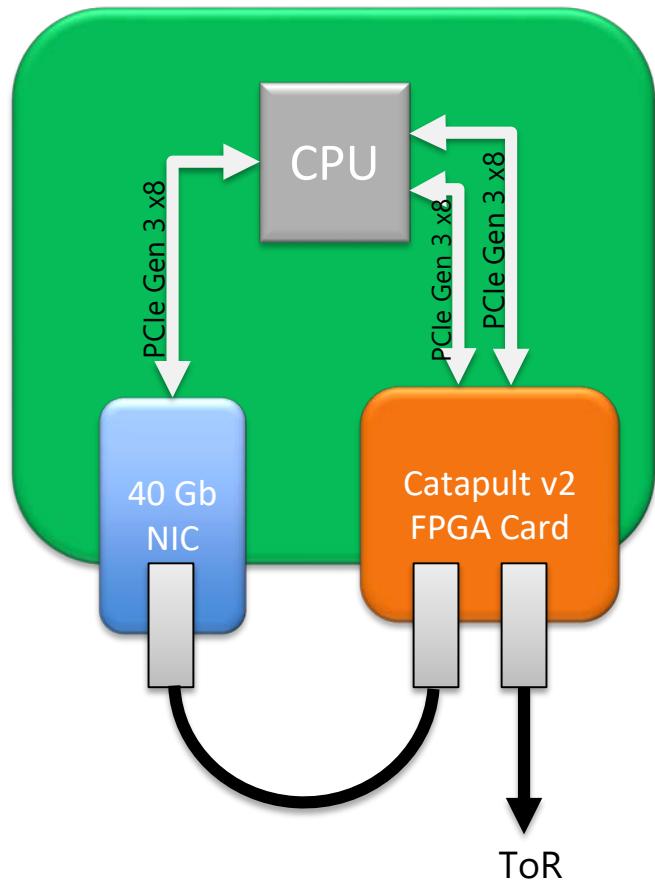
≈ 12 years?

- *Infrastructure* acceleration benefits common software and services

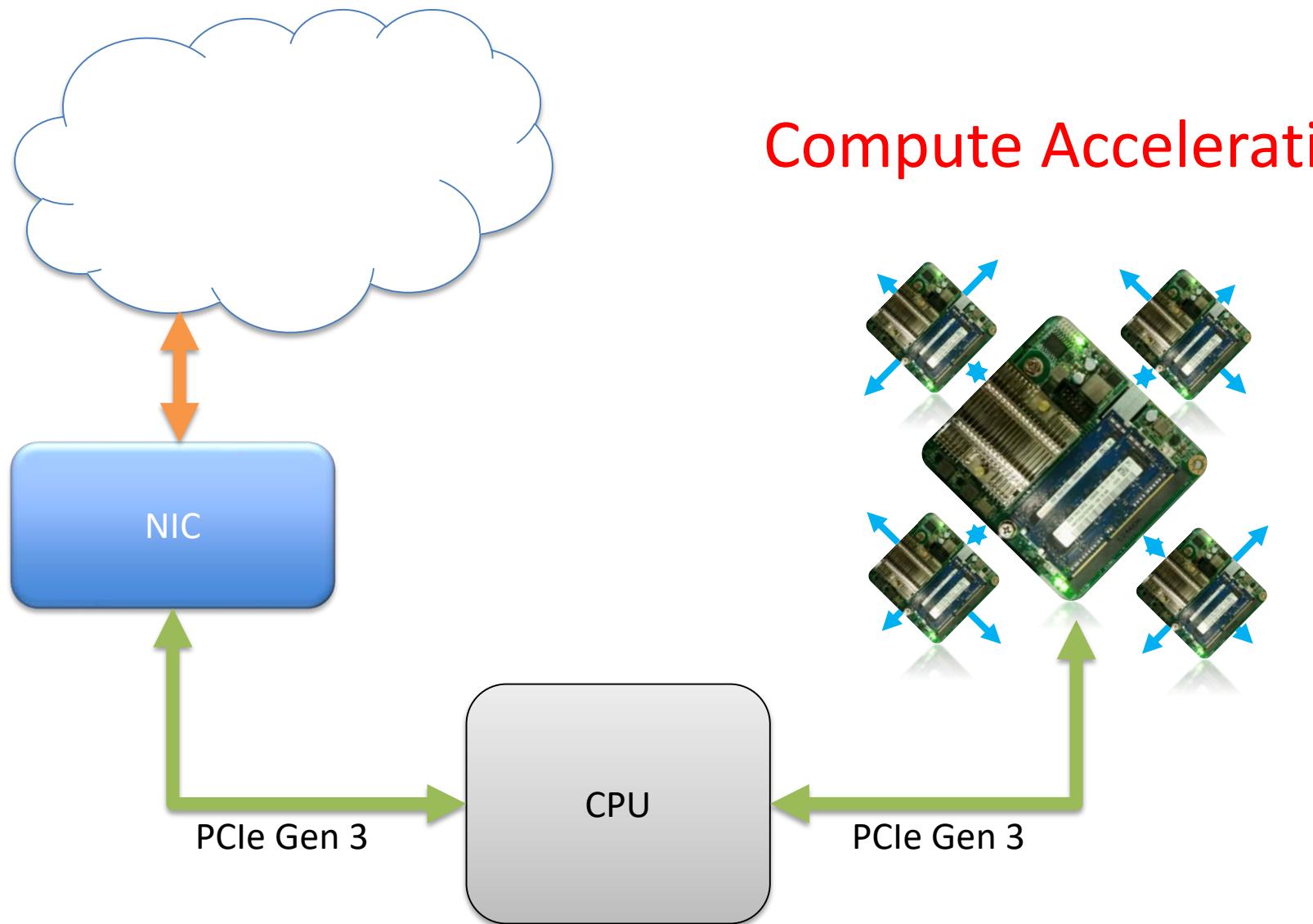
- Network offload and processing
- Encryption / Compression
- Security

- BOTH are critical when dealing with diverse cloud workloads

# Catapult v2 – Bump in the Wire

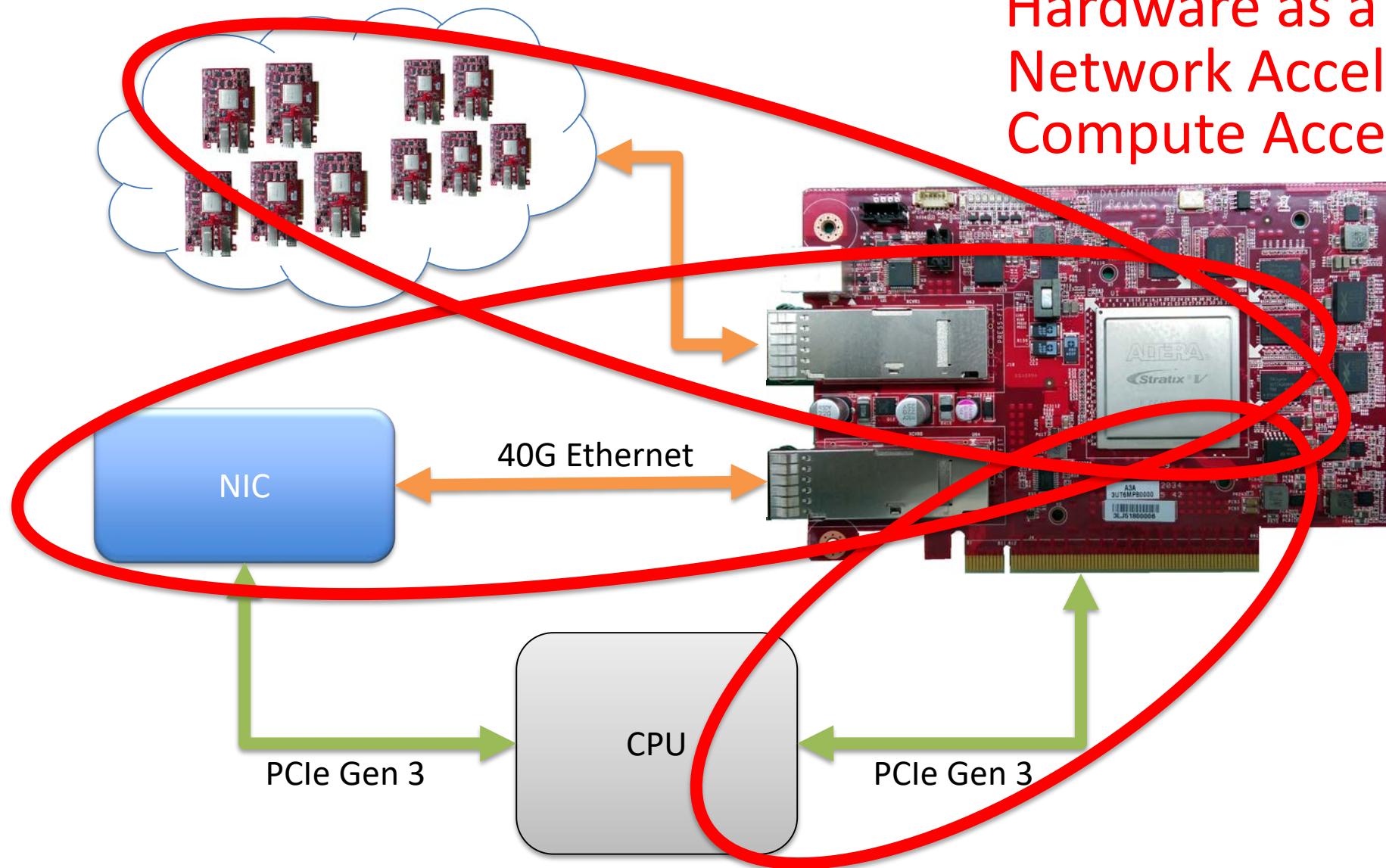


# Catapult v1 Architecture

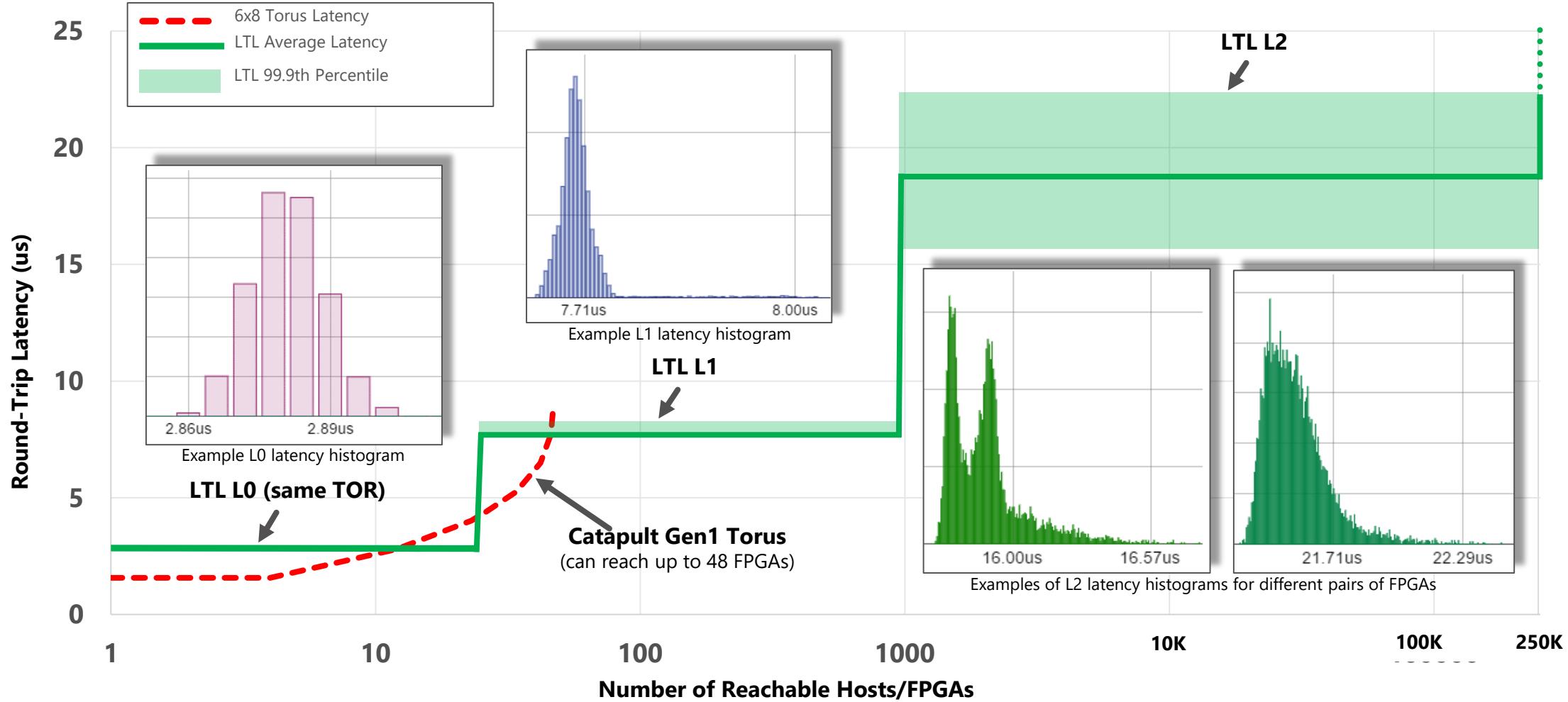


# Bump-in-the-wire Architecture

Hardware as a Service  
Network Acceleration  
Compute Acceleration



# Network Latencies



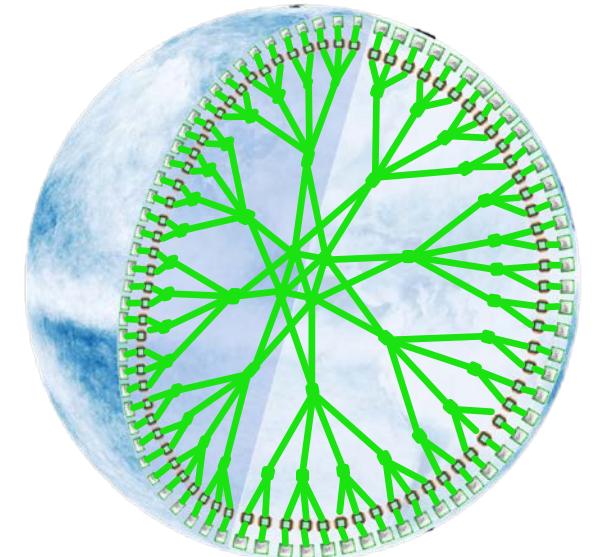
# Inter-FPGA Communication

- LTL -- Lightweight Transport Layer
- A Low-latency, Reliable, Connection-based communication channel for FPGA-to-FPGA messaging over standard Ethernet network
- Send-side buffering and retransmit until recv. ACK
- Built in send-side queueing mechanism to handle serialization of messages during contention
- FPGAs can communicate without any CPU intervention

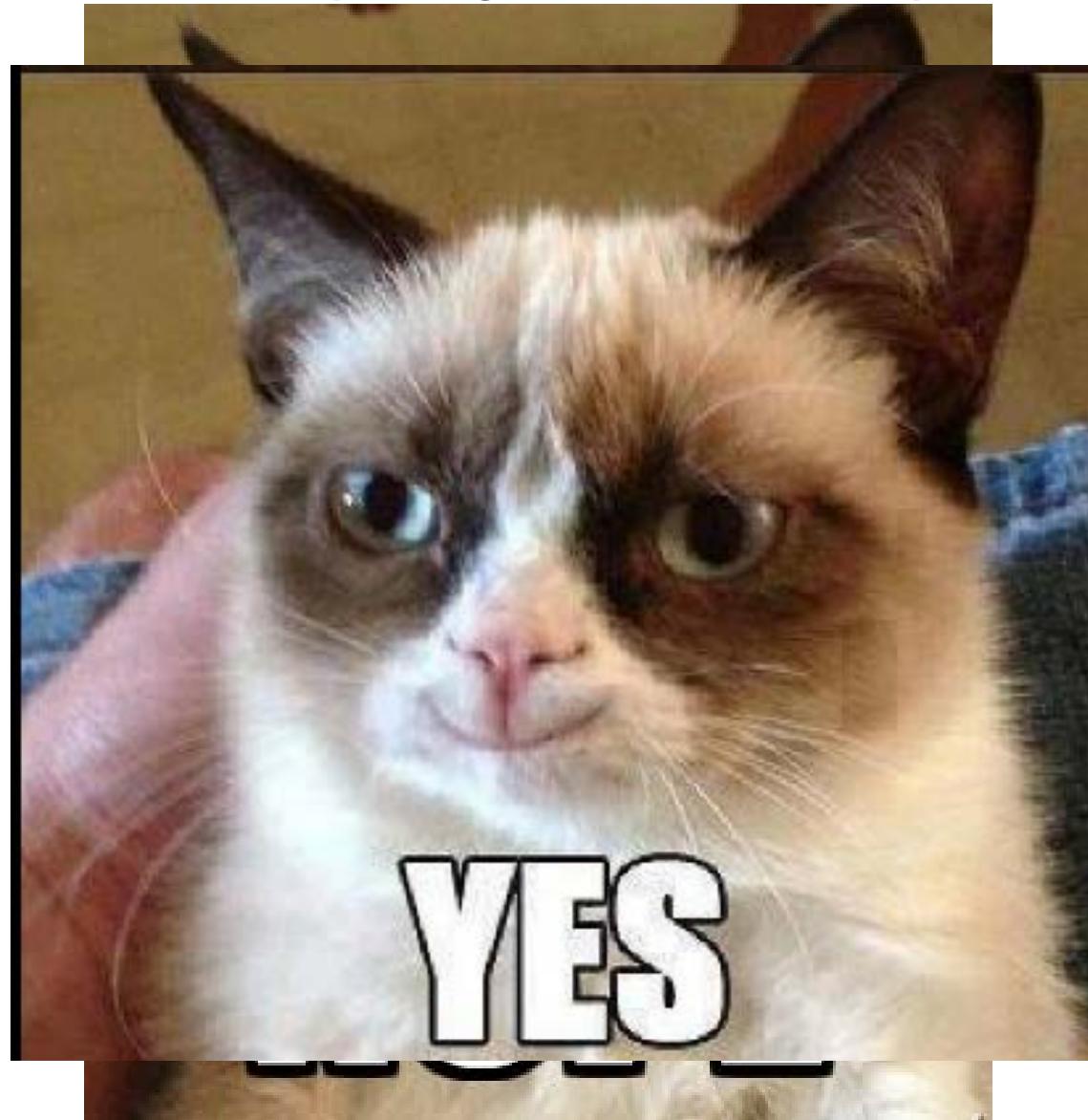
# Benefits of Bump-in-the-Wire

- Compute & Infrastructure Acceleration with one board
- A global hyperscale FPGA fabric – 100k+ FPGAs
- Improved Robustness & Fault Tolerance
- Fewer hops between FPGAs
- Independent of physical location
- Customized network hardware & protocols
- Allows sharing of underutilized FPGA resources

*All while retaining hardware homogeneity!*



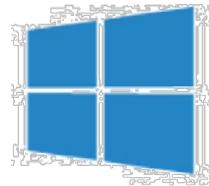
Was this Catapult deployed into production?





- **FPGAs Included in every new server for all major services**
- Deployed across 15 countries and 5 continents
- Already in large scale production in both Bing and Azure

# What workloads run well?



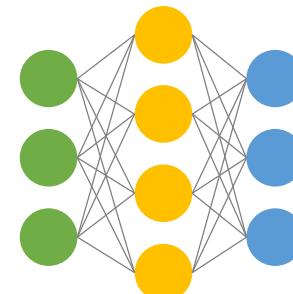
Microsoft Azure



Compression



Encryption

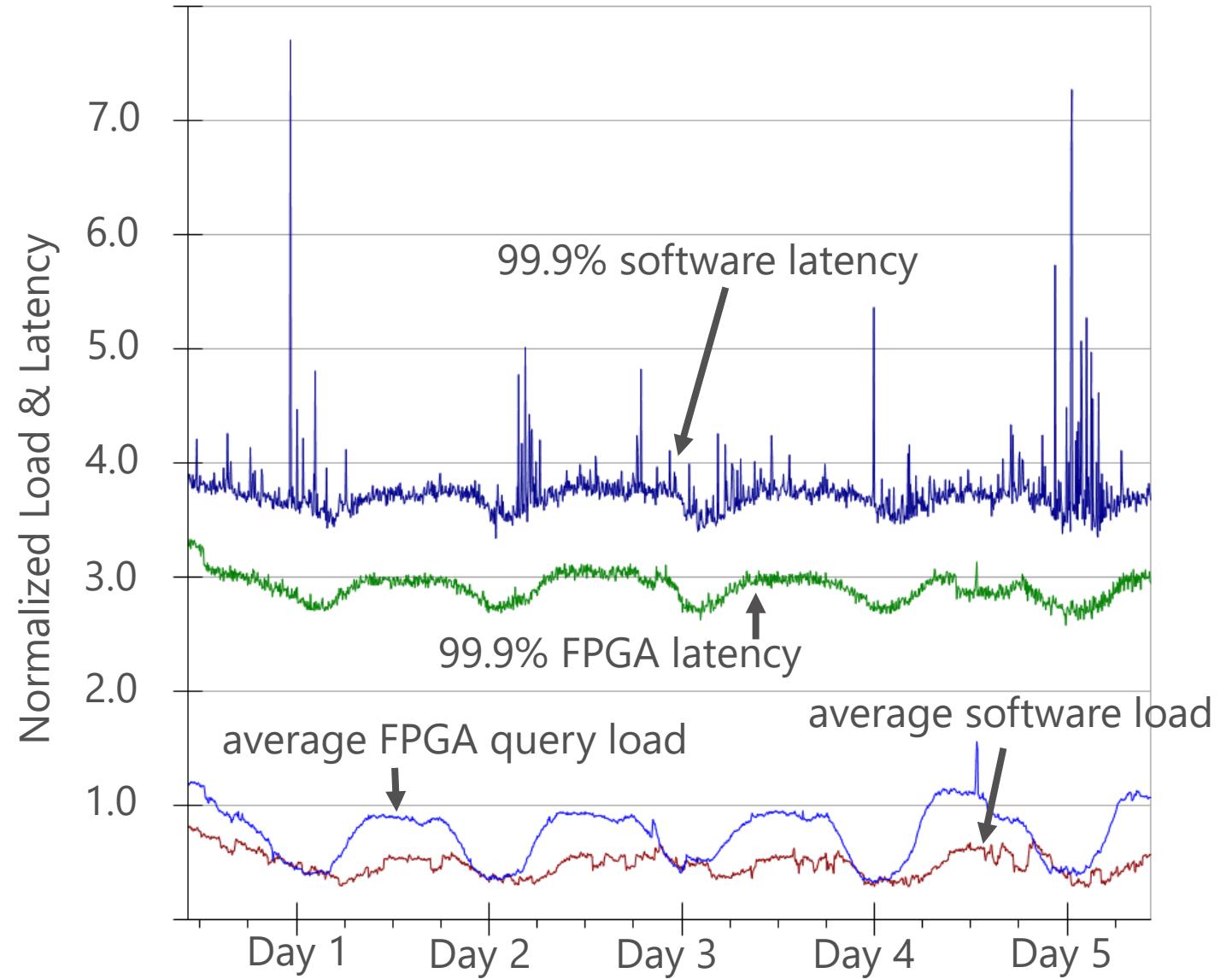


DNNs

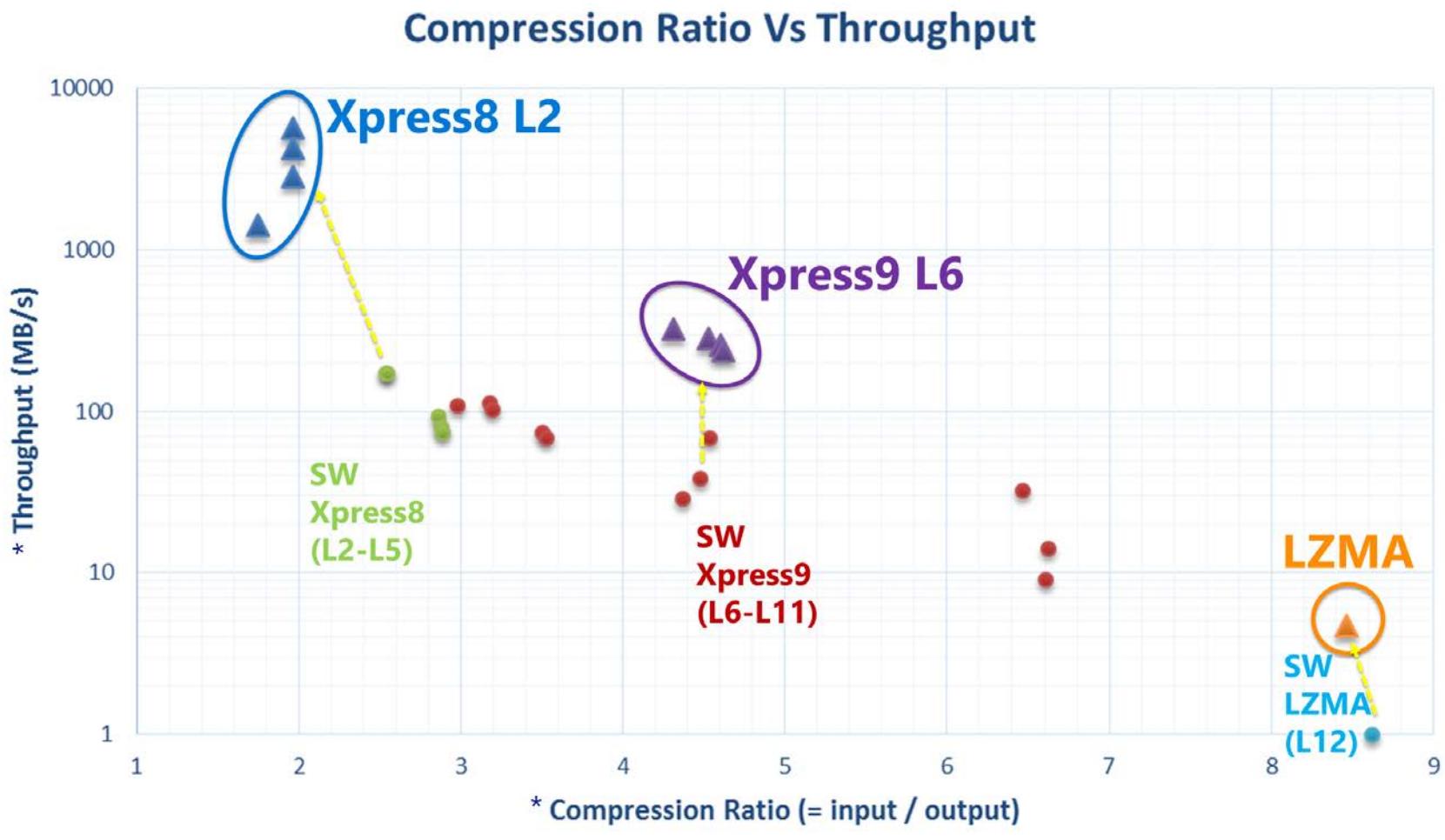
# Compute Acceleration -- Bing Ranking



- 2x Faster at 2x higher load
- Much lower variance



# Data Compression



\*- Measured on Canterbury dataset

Xpress8 L2 (5.6GB/s)  
30x throughput  
20% compression loss  
**In-line compression**

Xpress9 L6 (300MB/s)  
4x throughput  
No compression loss  
**Short/mid-term data**

LZMA (5MB/s)  
5x throughput  
5% compression loss  
**Long-term storage**

# Homomorphic Encryption

- Allows computation on data without revealing the data itself to the entity performing the computation
- Premium example: cloud computing
  - Clients encrypt data and store encrypted data in the cloud
  - The cloud server performs computation but an attacker (malicious admin, hacker, intelligence agency) cannot see the actual data
- Only user can interpret the result

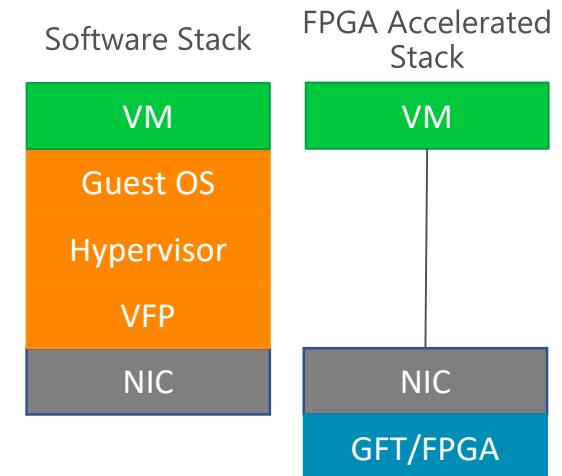
Author	Architecture	Parameter	Mult	Add
Catapult	FPGA (Stratix 5)	YASHE, n=16384	49 ms	1 ms
[LN'14]	3.5 GHz Intel i7	YASHE, n=4096	49 ms	0.7 ms
[RJVDV'15]	FPGA (Virtex-7)	YASHE, n=32768	112 ms	0.17 ms

# Infrastructure Acceleration

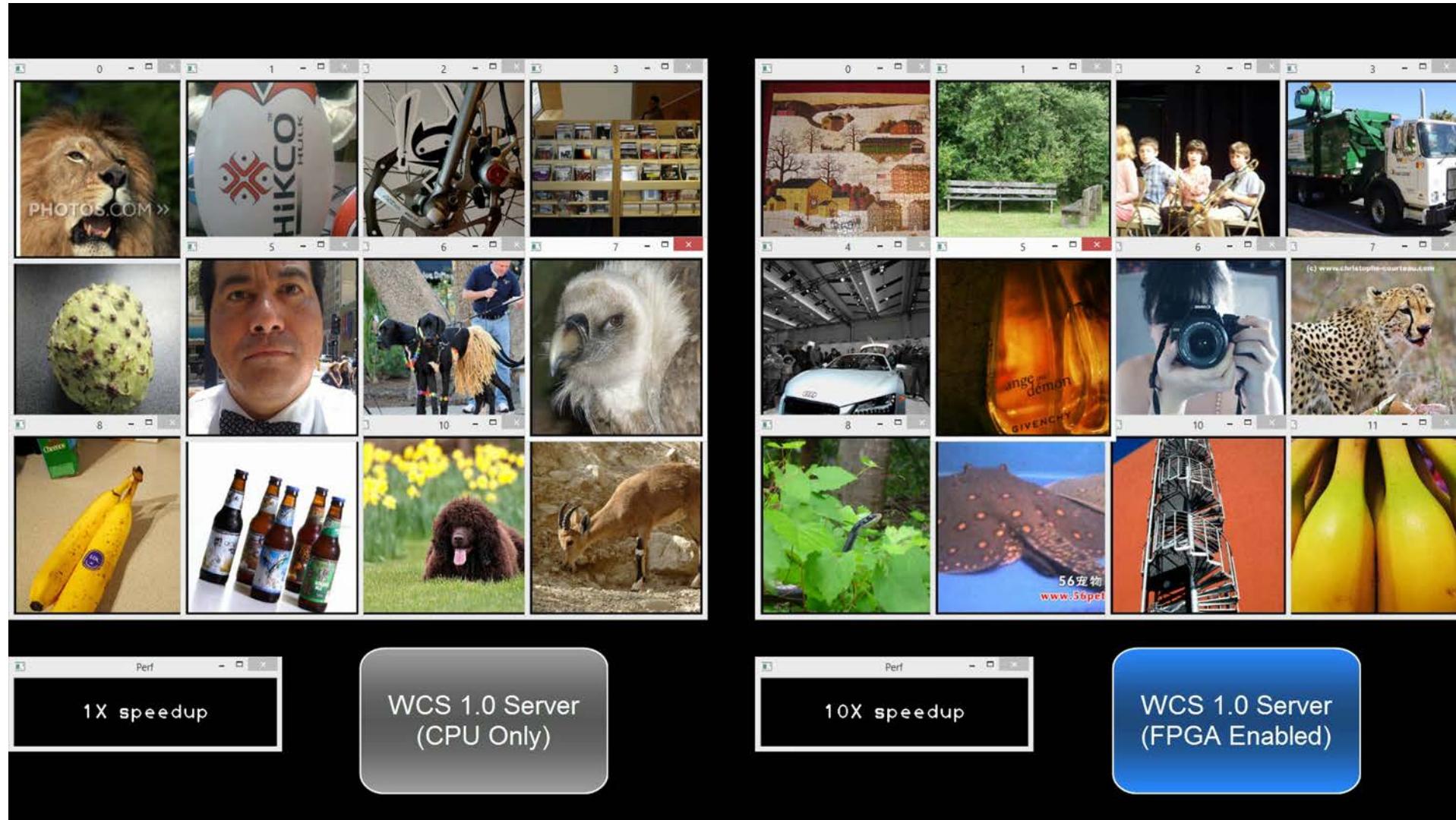


## SmartNIC: SDN and Crypto offload

- Generic Flow Table (GFT) rule based packet rewriting
- Enhanced network security
- 10x latency reduction vs software, CPU load now <1 core
- 25Gb/s throughput at 25 $\mu$ s latency – **the fastest cloud network**



# Deep Learning -- Image Classification via CNN

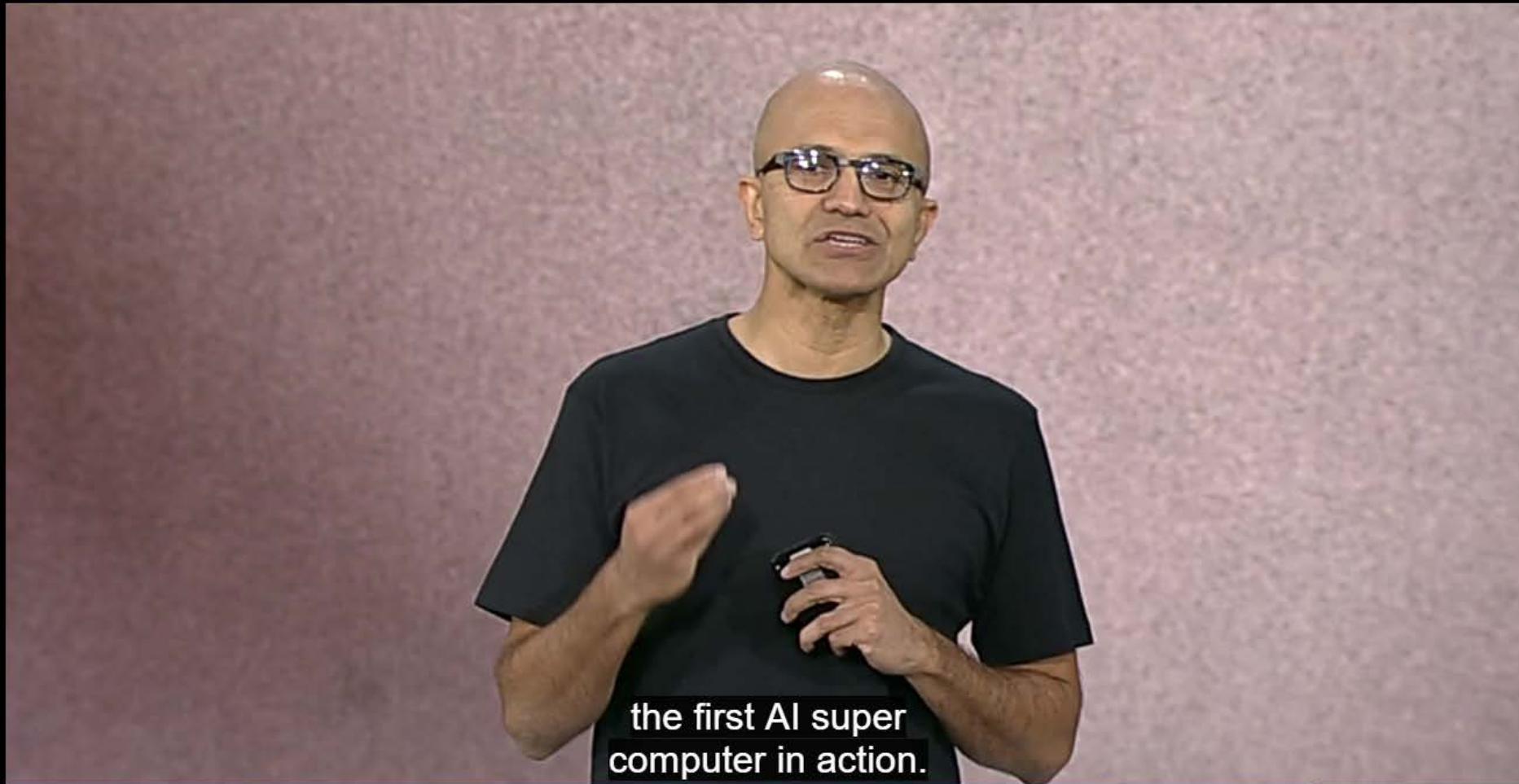


2x 8-core 2.10 GHz Xeon (95W TDP)

One Stratix V D5 FPGA (25 W)

# Microsoft Ignite

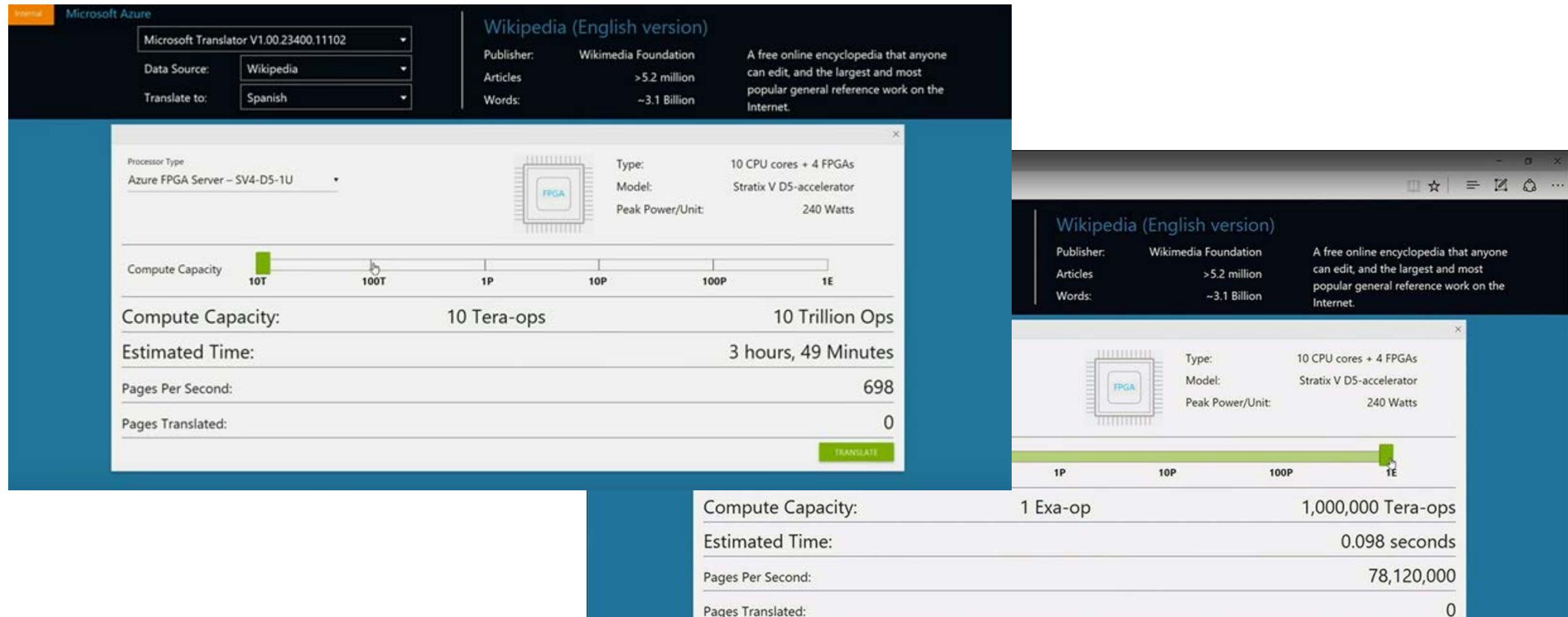
September 26–30, 2016, Atlanta, GA



0:53:40 / 1:02:47



# AI – Automatic Translation



- >10x the AI capacity of the world's largest supercomputers with Catapult v2
- Next generation is more than 3x more powerful

## NEWS

# Microsoft Claims Fastest Network in the Cloud

*Microsoft CEO Satya Nadella demonstrated some of the AI supercomputing capabilities in its Azure public cloud that make it now among the fastest cloud services available. The secret sauce is the use of field-programmable gate arrays.*

By Jeffrey Schwartz ■ 09/30/2016

Microsoft CEO Satya Nadella demonstrated some of the AI supercomputing capabilities of the company's Azure platform. He said, in his keynote this week at Microsoft Ignite in Atlanta, that the company two years ago started upgrading every node in its Azure public cloud with software-defined network (SDN) infrastructure, developed using field-programmable gate arrays (FPGAs).



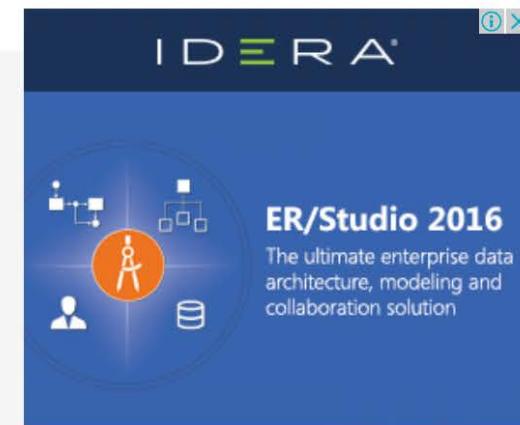
The result is that Microsoft's Azure public cloud fabric is now built on a 25 gigabit-per-second

# Microsoft's Project Catapult is why Intel bought FPGA-maker Altera for \$16.7 billion last year

By Shawn Knight on September 26, 2016, 4:45 PM



Intel last year acquired FPGA-maker Altera for \$16.7 billion in cash, the chipmaker's largest purchase in history. As it turns out, Microsoft played a key role in Intel's decision to make the purchase.



## MOST POPULAR



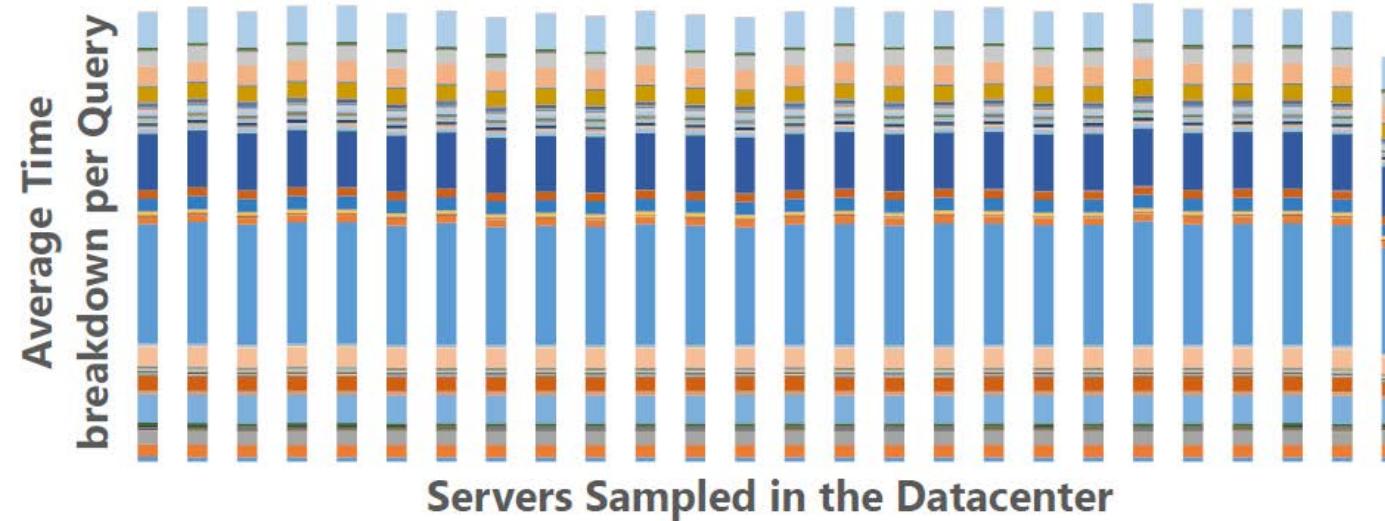
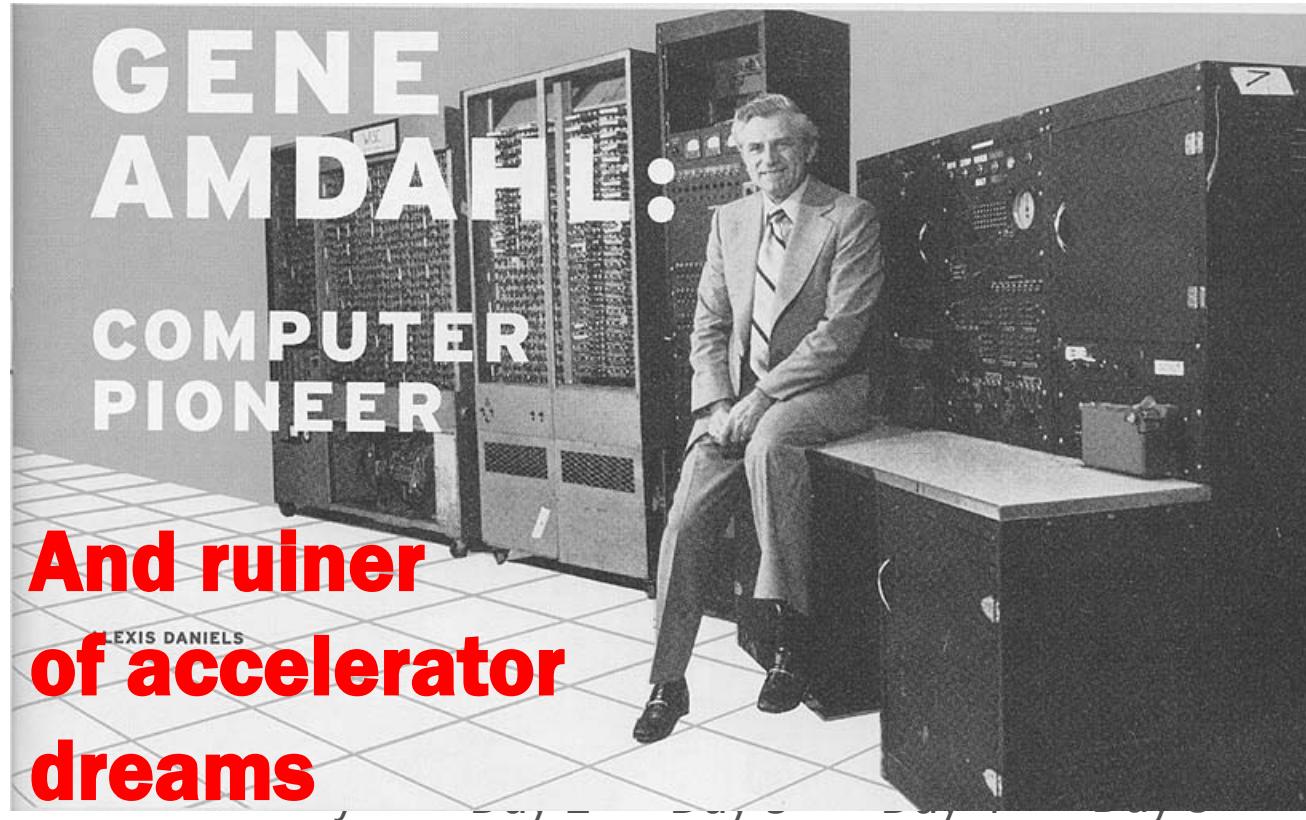
The Best PC Speakers

# WHAT COULD POSSIBLY GO WRONG?



# How do you program FPGAs?

- 10:1 or larger ratio of SW to HW programmers
- Verilog is the predominant programming language
- High-level synthesis (SDAccel, OpenCL, ROCCC, LegUp...) make it a little easier
  - Debugging still a challenge
  - Often requires platform-specific pragmas for good performance, which requires detailed knowledge of the FPGA architecture
- So far, most successful model is a custom contract between HW/SW, and still programming in Verilog

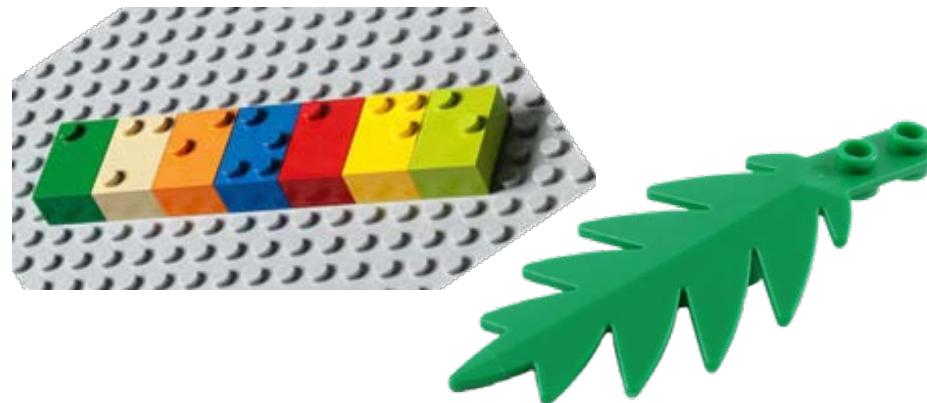


# Usage Models

- Could allow users to have raw access to the FPGAs
  - Amazon EC2 F1
- High-Level Synthesis tools make this easier
- More common is a library of services built on top of FPGAs
  - DNN computation service, linear algebra, web search (Bing)...
- Infrastructure acceleration enables gradual migration to FPGAs

# What am I worried about?

- I don't think the biggest problem is software engineers being able to program FPGAs
- I think our biggest problem is that we're going to make software engineers fight old battles
  - Libraries, linkers, backwards compatibility



# Catapult Academic Program

- Donated 3 full racks of machines at TACC for research (96 machines per rack)
- Individual boards are available for in-house development use
- Very little effort to move from the academic cluster to the production machines
- See:  
<http://research.microsoft.com/catapult>  
for details

**ALTERA.**

 **Microsoft**



# Conclusion

- Specialization with FPGAs is critical to the future Cloud
- FPGAs are harder to program, and improving that will greatly improve efficiency for Big Data / Cloud apps
- FPGAs allow optimization of both compute and I/O operations, so think beyond the core application
- What can you build with your global pile of Legos?





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