What is distributed computing?

The first demonstration of how to build really large Internet sites out of clusters of computers was done by:
(a) Stanford
(b) Berkeley
(c) Yahoo!
(d) Google
(e) IBM
NOW-0
1994
Four HP-735’s

NOW-1
1995
32 Sun SPARC-stations

NOW-2
1997
60 Sun SPARC-2

A Google datacenter built c.2005 would be designed to house approximately _______ computers.

(a) 1,000
(b) 5,000
(c) 10,000
(d) 50,000
(e) 100,000

Challenge: how do you program a NOW? (or: what is it good for?)

The Killer App for NOWs

• Prof. Eric Brewer, Armando Fox, Steve Gribble, Paul Gauthier, Yatin Chawathe: *Cluster-Based Scalable Network Servers* in Symposium on Operating Systems Principles, 1997
• *Non*-goal: build best/fastest search engine
  – But led to Inktomi, first *truly scalable* search engine that took advantage of NOW ideas
• Goal: show general techniques for programming NOW’s for Internet services
Access Is the Killer App!
UC Berkeley, 1994-1999

- Project Daedalus: Profs. Katz & Brewer
- Data, services in infrastructure
  - search, email, personal comms, productivity...
- Mobile access anywhere, anytime
- Many “firsts”:
  - server architecture with auto-scaling
  - cluster-based Internet service: Inktomi
  - mobile Web: TopGun Wingman on Palm

Challenge: deploying the service!

2005: Datacenter is new “server”

- “Program” => Web search, email, map/GIS, ...
- “Computer” => 1000’s computers, storage, network
- Warehouse-sized facilities and workloads

photos: Sun Microsystems, CNET, & datacenterknowledge.com

RAD Lab 5-year Mission

Enable 1 person to develop, deploy, operate next-generation Internet application

- Key enabling technology: Statistical machine learning
- Highly interdisciplinary faculty & students
  - 7 faculty across CS, from theory to systems
  - 2 postdocs, ~30 PhD students, ~5 undergrads

Utility Computing Arrives

- Amazon Elastic Compute Cloud (EC2)
- “Compute unit” rental: $0.08-0.80/hr.
  - 1 CU = 1.0-1.2 GHz 2007 AMD Opteron/Xeon core

<table>
<thead>
<tr>
<th>&quot;Instances&quot;</th>
<th>Platform</th>
<th>Cores</th>
<th>Memory</th>
<th>Disk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small - $0.10/hr</td>
<td>32-bit</td>
<td>1</td>
<td>1.7 GB</td>
<td>160 GB</td>
</tr>
<tr>
<td>Large - $0.40/hr</td>
<td>64-bit</td>
<td>4</td>
<td>7.5 GB</td>
<td>850 GB – 2 spindles</td>
</tr>
<tr>
<td>XLarge - $0.80/hr</td>
<td>64-bit</td>
<td>8</td>
<td>15.0 GB</td>
<td>1690 GB – 3 spindles</td>
</tr>
</tbody>
</table>

- No up-front cost, no contract, no minimum
- Billing rounded to nearest hour; pay-as-you-go storage also available
- A new paradigm for deploying services?

But...
What is cloud computing, exactly?
“It’s nothing (new)”

“...we’ve redefined Cloud Computing to include everything that we already do... I don’t understand what we would do differently ... other than change the wording of some of our ads.”

– Larry Ellison, CEO, Oracle
(Wall Street Journal, Sept. 26, 2008)

Above the Clouds: A Berkeley View of Cloud Computing

aboveclouds.cs.berkeley.edu

- 2/09 White paper by RAD Lab PI's and students
- Goal: stimulate discussion on what's really new
  - Clarify terminology
  - Comparison with conventional computing
  - Identify challenges & opportunities
- Why can we offer new perspective?
  - Strong engagement with industry
  - Users of cloud computing in our own research and teaching
- Over 60,000 downloads

Above The Clouds Impact

• Research collaborations/hires: Amazon, Google, Microsoft, Twitter, Facebook, Cloudera, Yahoo!...
• Invited presentations/advice
  - Google, Fujitsu, IBM, HP, Microsoft, SAP, Juniper, ...
  - World Economic Forum
  - Nat’l Academy of Engineering
  - OpenCirrus Summit
  - UCB Office of the CIO
  - UC Systemwide Cloud Computing Task Force

UCB is academic leader in cloud computing in both research & education

What is it? What’s new?

• Old idea: Software as a Service (SaaS)
  - Software hosted in the infrastructure vs. installed on local servers or desktops; dumb (but brawny) terminals
• New: pay-as-you-go utility computing
  - Illusion of infinite resources on demand
  - Fine-grained billing: release == don’t pay
  - Earlier examples: Sun, Intel Computing Services — longer commitment, more $$$/hour, no storage
  - Public (utility) vs. private clouds

Why Now (not then)?

• The Web “Space Race”: Build-out of extremely large datacenters (10,000's of commodity PCs)
• Driven by growth in demand (more users)
  - Infrastructure software: e.g., Google File System
  - Operational expertise
  - Discovered economy of scale: 5-7x cheaper than provisioning a medium-sized (100's machines) facility
• More pervasive broadband Internet
• Free & open source software

• How much data per month, approximately, is processed through Google’s BigTable storage system?
  (a) 1 TB (1,000 GB)
  (b) 100 TB
  (c) 1 PB (1,000 TB)
  (d) 100 PB
  (e) 1 EB (exabyte = 1,000 PB)
Cloud Economics 101

- Static provisioning for peak - wasteful, but necessary for SLA

<table>
<thead>
<tr>
<th>Machines</th>
<th>Demand</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>5</td>
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</tbody>
</table>

"Statically provisioned" data center

"Virtual" data center in the cloud

Risk of Under Utilization

- Underutilization results if "peak" predictions are too optimistic

<table>
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</thead>
<tbody>
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<td>1</td>
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Static data center

Unused resources

Risks of Under Provisioning

- Lost revenue
- Lost users

<table>
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</table>

What can you do with this?

Cost Associativity

- 1,000 CPUs for 1 hour same price as 1 CPU for 1,000 hours
- Washington Post converted Hillary Clinton’s travel documents to post on WWW
  - Conversion time: <1 day after released
  - Cost: less than $200
- RAD Lab graduate students demonstrate improved MapReduce scheduling—on 1,000 servers

Risk transfer

- 2001: CNN home page meltdown on 9/11
  - ~10x traffic increase in ~15 minutes
  - result: site had to go offline
- 2008: Animoto
  - traffic doubled every 12 hours for 3 days when released as Facebook plug-in
  - Scaled from 50 to >3500 servers
  - ...then scaled back down
Indexing the Web

To be or not to be... or a better fool...

Map & Combine

MapReduce in Practice

• Example: spam classification
  – training: 10^7 URLs x 64KB data each = 640GB data
  – One heavy-duty server: ~270 hours
  – 100 servers in cloud: ~3 hours (~$255)

• Rapid uptake in other scientific research
  – Large-population genetic risk analysis & simulation (Harvard Medical School)
  – Genome sequencing (UNC Chapel Hill Cancer Ctr)
  – many others... so what's the downside?

Challenges & Opportunities

• Challenges to adoption, growth, & business/policy models
• Both technical and nontechnical
• Most translate to 1 or more opportunities
• Complete list in paper; I'll discuss subset

Challenge: Cloud Programming

• Challenge: exposing parallelism
  – MapReduce relies on “embarrassing parallelism”
  – Programmers must (re)write problems to expose this parallelism, if it's there to be found
  – Tools still primitive, though progressing rapidly

Challenge: Big Data

<table>
<thead>
<tr>
<th>Application</th>
<th>Data generated per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNA Sequencing (Illumina HiSeq</td>
<td>1 TB</td>
</tr>
<tr>
<td>machine)</td>
<td></td>
</tr>
<tr>
<td>Large Synoptic Survey Telescope</td>
<td>30 TB; 400 Mbps sustained data rate between Chile and NCSA</td>
</tr>
<tr>
<td>Large Hadron Collider</td>
<td>60 TB</td>
</tr>
</tbody>
</table>

• Challenge: Long-haul networking is most expensive cloud resource, and improving most slowly
• Copy 8 TB to Amazon over ~20 Mbps network  => ~35 days, ~$800 in transfer fees
• How about shipping 8TB drive to Amazon instead?  => 1 day, ~$150 (shipping + transfer fees)

Web services in the cloud

Cloud in Education

1. Berkeley research culture: integrate leading research into teaching at all levels
2. RAD Lab need for “killer apps” to show off infrastructure

Current efforts (student counts approximate):
- Great Ideas in Computer Architecture (reinvented Fall 2010): 190 students
- Software Engineering for SaaS (in its 4th iteration): 50+50+50+70 students
- Operating Systems: 70 students
- Intro. Data Science (Spring 2010): 30
- Adv. topics in HCI: 20 students
- Natural language processing: 20 students

AWS is a great fit for courses...

- New undergraduate teaching opportunities
  - SaaS: make a database fall over—would need 200 servers for ~20 project teams
  - deploy projects publicly, many continue after course
- Better use of resources
  - Heavy usage right before lab deadlines

Success stories

- Cloud computing democratizes access to “supercomputer-class” capability
  - All you need is a credit card
- Puts students, academia on more level playing field to have high impact in industry
- The next Google, eBay, Amazon, etc. can come from a small team of entrepreneurs even without heavy dose of $$ up front

Summary

- Going back to NOW...
  - 2000: using medium-sized clusters for Internet services => several PhD’s
  - 2010: CS169 students do it in 6-8 weeks and deploy on cloud computing
  - 2020: ?

Thank you!