CSE 451: Operating Systems
Winter 2017

Module 24
Distributed Systems

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Allen Center 476

What is a "distributed system"?

- Nearly all systems today are distributed in some way
  - they use email
  - they access files over a network
  - they access printers over a network
  - they're backed up over a network
  - they share other physical or logical resources
  - they cooperate with other people on other machines
  - they access the web
  - they receive video, audio, etc.

Loosely-coupled systems

- Earliest systems used simple explicit network programs
  - FTP (rcp): file transfer program
  - telnet (rlogin/rsh): remote login program
  - mail (SMTP)
- Each system was a completely autonomous independent system, connected to others on the network

- Even today, most distributed systems are loosely-coupled (although not that loosely!):
  - each CPU runs an independent autonomous OS
  - computers don’t really trust each other
  - some resources are shared, but most are not
  - the system may look differently from different hosts

Closely-coupled systems

- A distributed system becomes more “closely-coupled” as it
  - appears more uniform in nature
  - runs a “single” operating system
  - has a single security domain
  - shares all logical resources (e.g., files)
  - shares all physical resources (CPUs, memory, disks, printers, etc.)
- In the limit, a distributed system looks to the user as if it were a centralized timesharing system, except that it’s constructed out of a distributed collection of hardware and software components

Tightly-coupled systems

- A “tightly-coupled” system usually refers to a multiprocessor
  - runs a single copy of the OS with a single workload queue
  - has a single address space
  - usually has a single bus or backplane to which all processors and memories are connected
  - has very low communication latency
  - processors communicate through shared memory

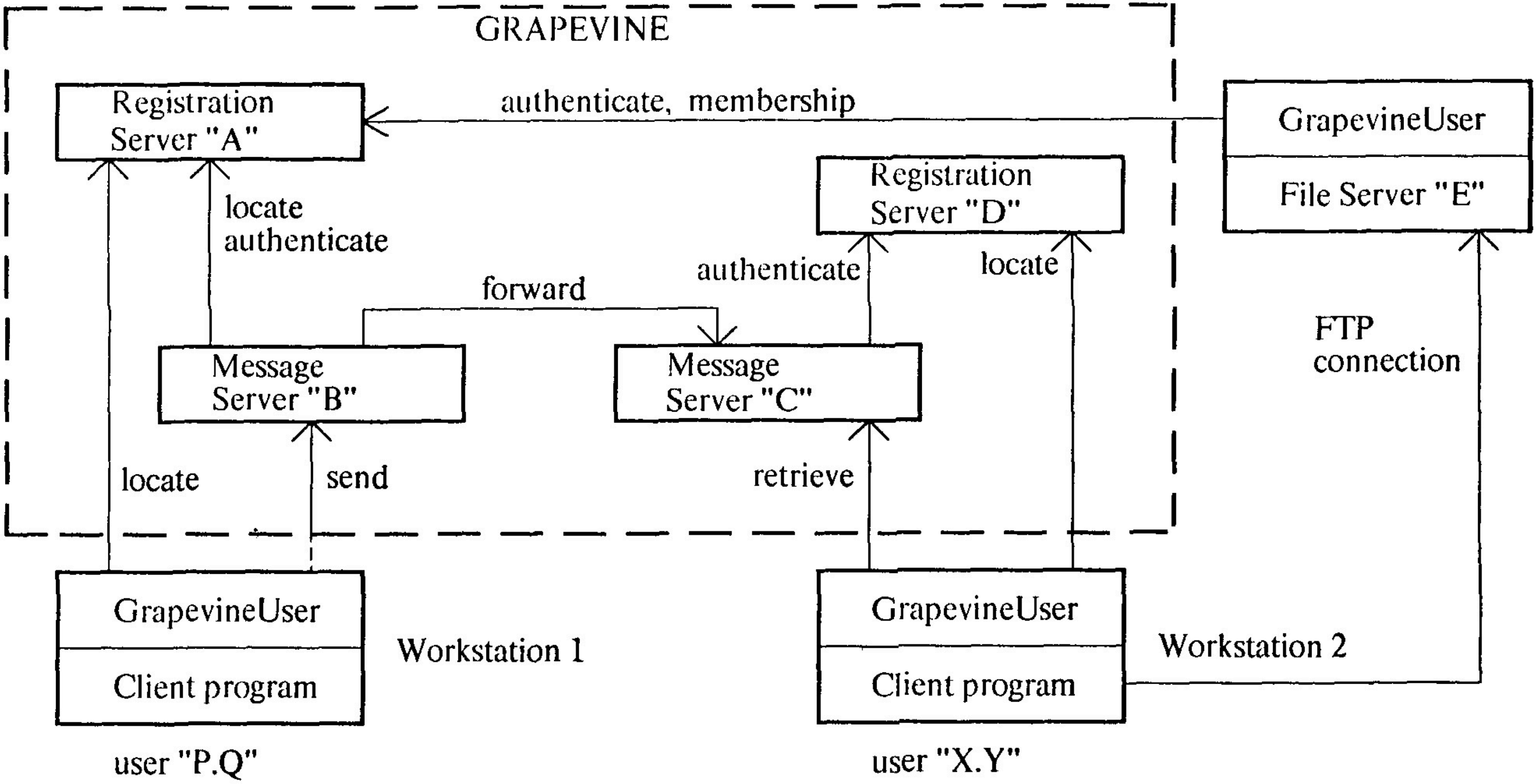
Some issues in distributed systems

- Availability (can you get it now?)
- Reliability (may you lose stuff permanently?)
- Performance (on a LAN, on a WAN, global)
- Scalability (can it grow modularly as you add users, without relying on ever-bigger/faster computers?)
- Transparency (how visible is the distribution to users?)
- Programming models (how visible is the distribution to programmers?)
- Communication models (messages, RPC, etc.)
- Security

Example: Grapevine distributed mail service

- Xerox PARC, 1980
  - cf. Microsoft Outlook/Exchange today!!!!!
- Goals
  - cannot rely on integrity of client
  - once the system accepts mail, it will be delivered
  - no single Grapevine computer failure will make the system unavailable to any client either for sending or for receiving mail
- Components
  - GrapevineUser package on each client workstation
  - Registration Servers
  - Message Servers
- Implementation: Remote Procedure Call

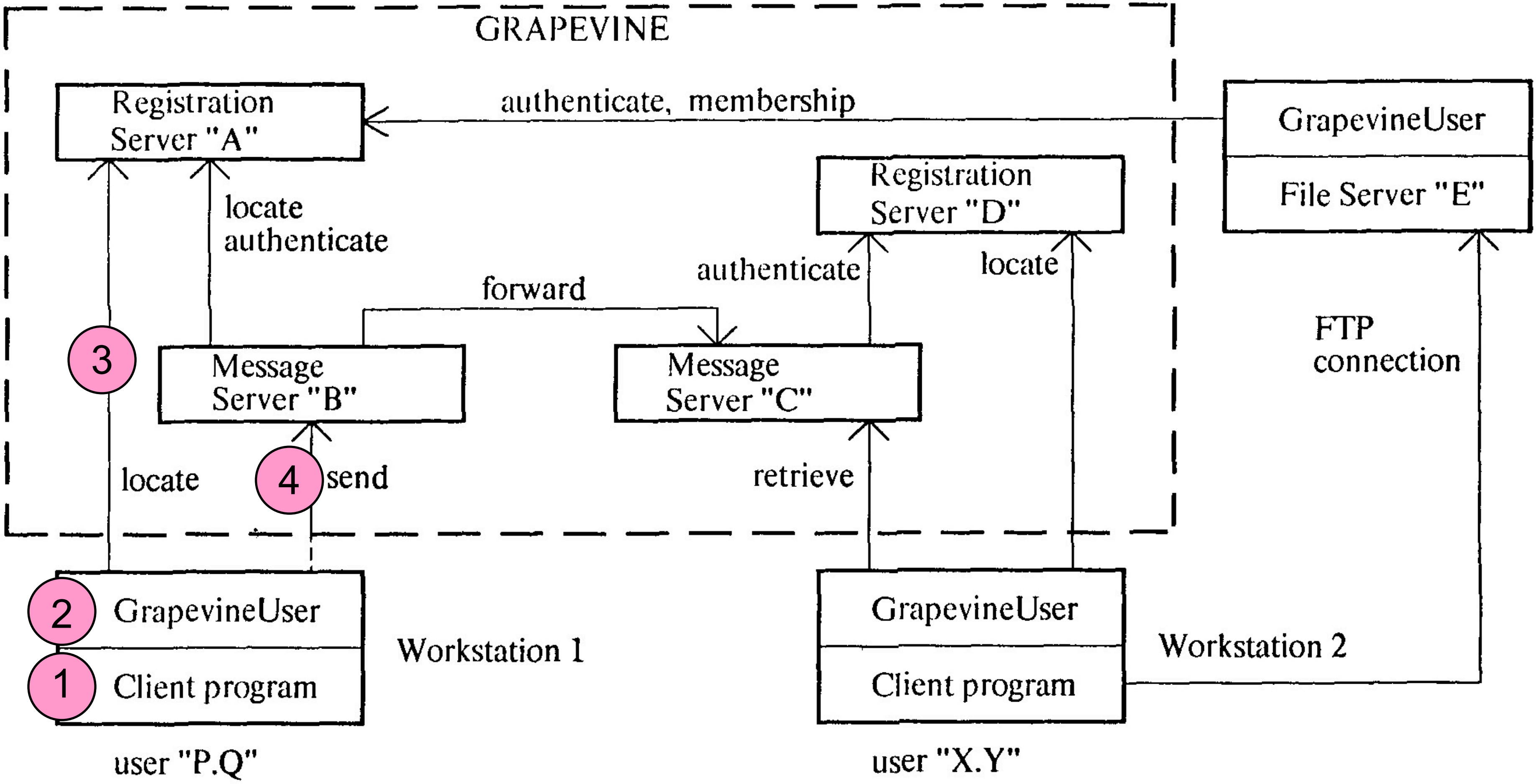
Grapevine: Functional diagram



Grapevine: Sending a message

- User prepares message using mail client
- Mail client contacts GrapevineUser package on same workstation to actually send message
- GrapevineUser package
  - Contacts any Registration Server to get a list of Message Servers
  - Contacts any Message Server to transmit message
    - presents source and destination userids, and source password, for authentication
      - Message Server uses any Registration Server to authenticate
    - sends message body to Message Server
      - Message Server places it in stable storage and acknowledges receipt

Grapevine: Functional diagram



Registries

- Actually, I lied: There's an additional step.
  - For scalability, users are partitioned into registries – "user 'P.Q'" is user P in registry Q.
  - Registries are replicated.
  - There is one registry that is replicated on every registration server: the registry of registries.
  - So, when I said:

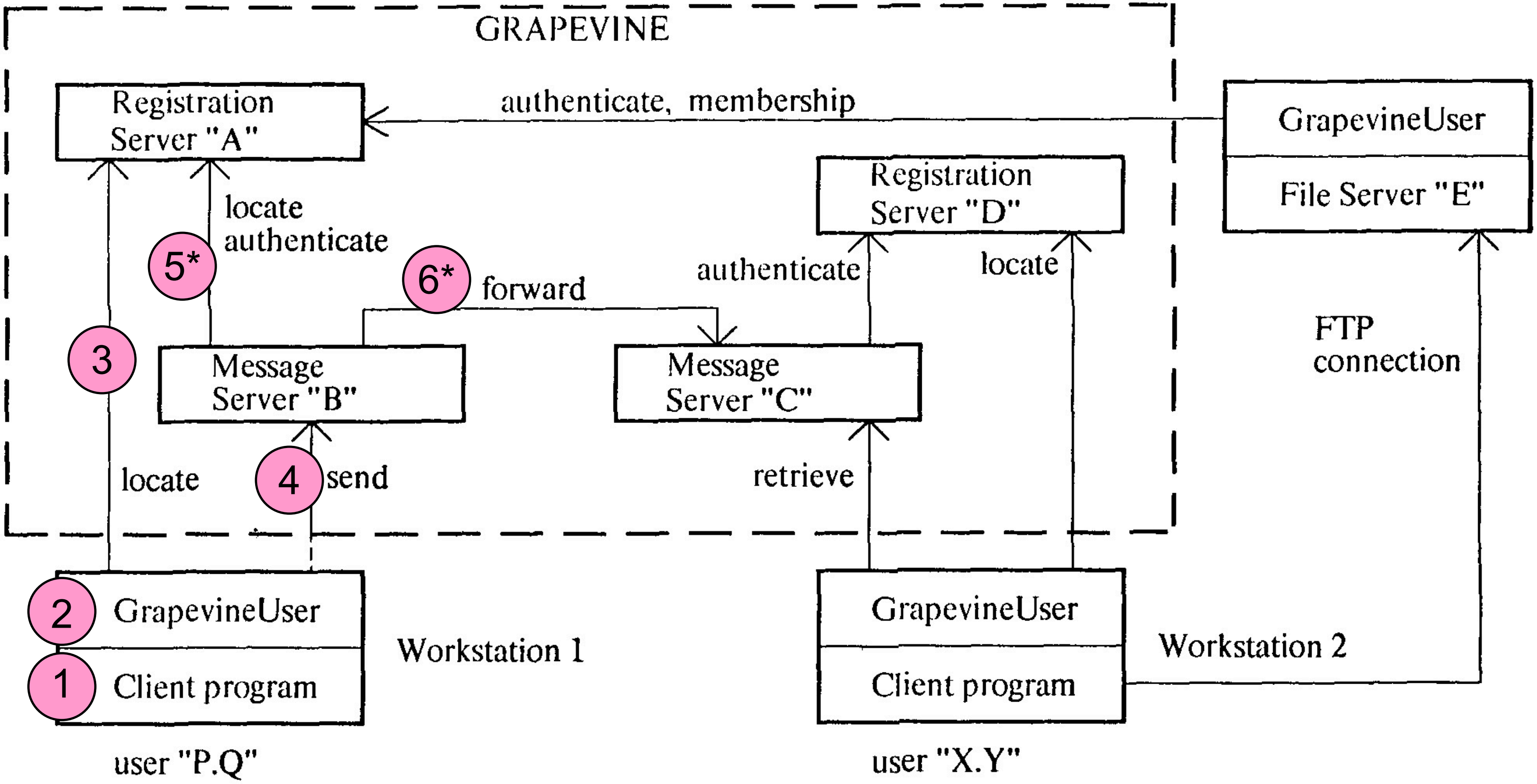
    Message Server uses any Registration Server to authenticate

    what actually happens is the Message Server contacts any Registration Server to obtain a list of those Registration Servers holding the registry of the user, then contacts one of those registration servers to authenticate the user

Grapevine: Transport and buffering

- For each recipient of the message, Message Server contacts any Registration Server to obtain list of Message Servers holding mail for that recipient
  - Same lie as before
- Sends a copy of the message to one of those Message Servers for that recipient

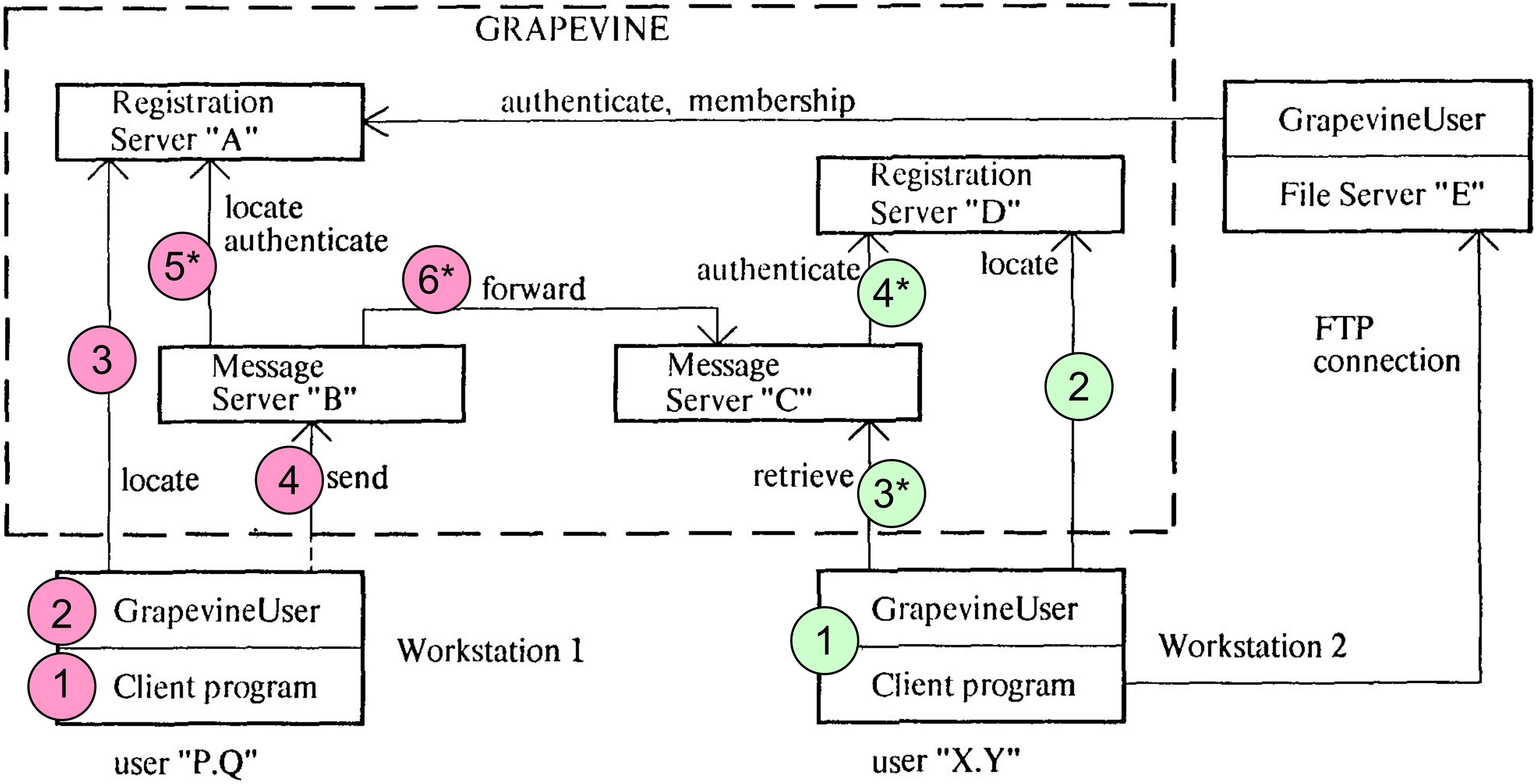
Grapevine: Functional diagram



Grapevine: Retrieving mail

- User uses mail client to contact GrapevineUser package on same workstation to retrieve mail
- GrapevineUser package
  - Contacts any Registration Server to get a list of each Message Server holding mail for the user ("inbox site")
    - Same lie as before
  - Contacts each of these Message Servers to retrieve mail
    - presents user credentials
      - Message Server uses any Registration Server to authenticate
    - acknowledges receipt of messages so that the server can delete them from its storage

Grapevine: Functional diagram



Grapevine: Scalability

- Can add more Registration Servers
- Can add more Message Servers
- Only thing that didn’t scale was handling of distribution lists
  - the accepting Message Server was responsible for expanding the list (recursively if necessary) and delivering to an appropriate Message Server for each recipient
  - some distribution lists contained essentially the entire user community
- Jeff Dean (Google) told us they don’t even think about more than two decimal orders of magnitude
  - fundamental design decisions will need to change
  - advances in technology will make it possible

Example: Google search infrastructure

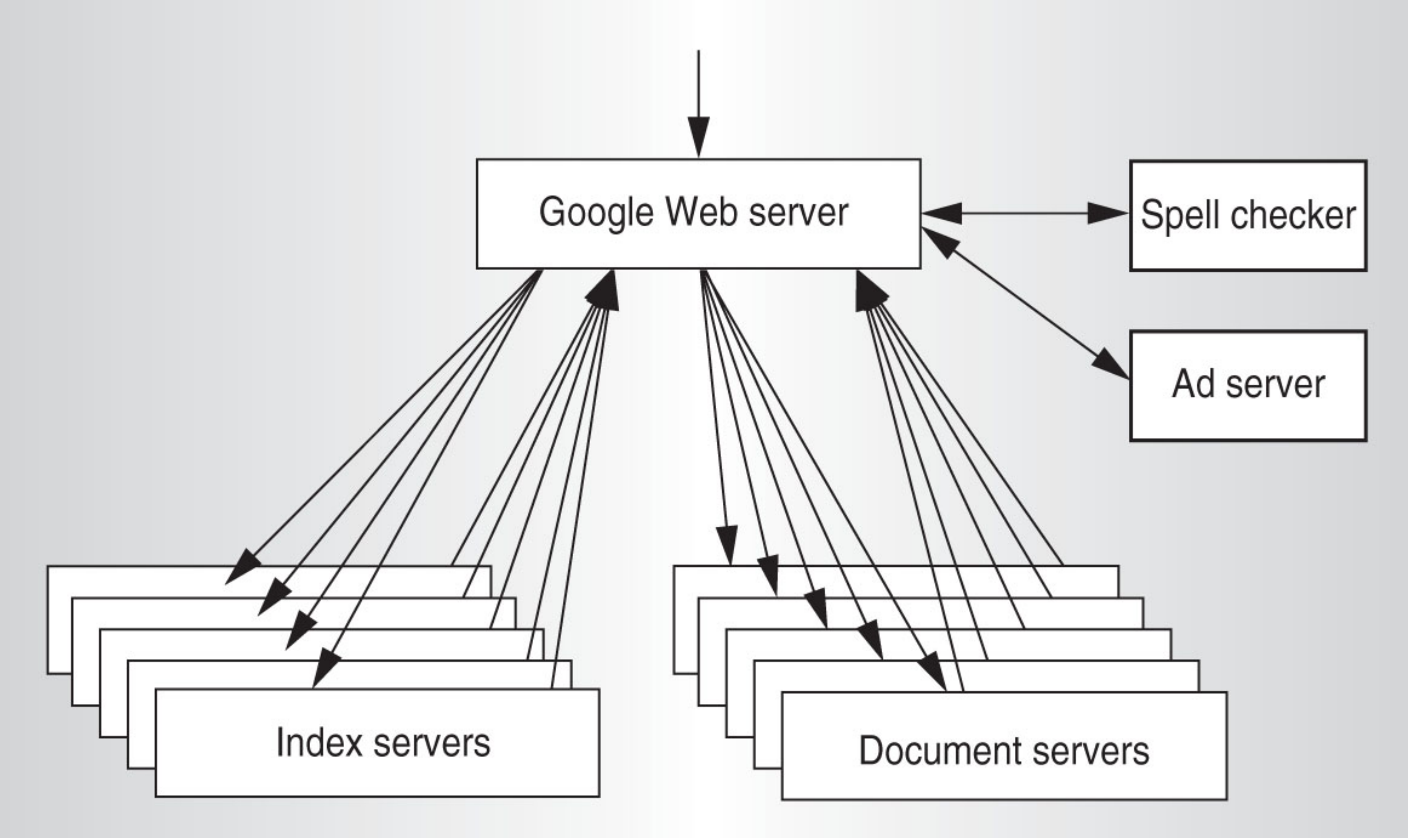
- It's likely that Google has several million machines
  - But let's be conservative – 1,000,000 machines
  - A rack holds 176 CPUs (88 1U dual-processor boards), so that's about 6,000 racks
  - A rack requires about 50 square feet (given datacenter cooling capabilities), so that's about 300,000 square feet of machine room space (more than 6 football fields of real estate – although of course Google divides its machines among dozens of datacenters all over the world)
  - A rack requires about 10kw to power, and about the same to cool, so that's about 120,000 kw of power, or nearly 100,000,000 kwh per month ($10 million at $0.10/kwh)
    - Equivalent to about 20% of Seattle City Light's generating capacity

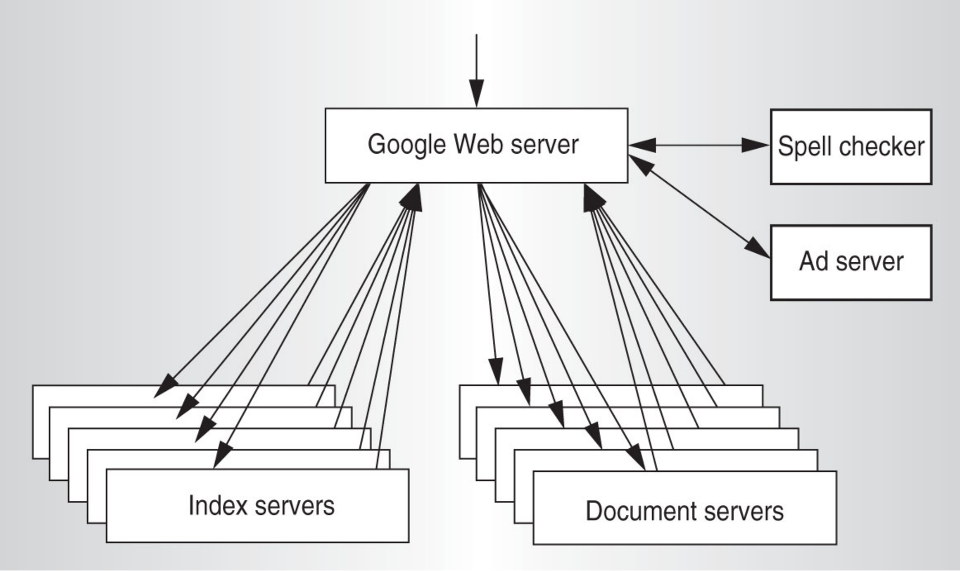
- There are multiple clusters (of thousands of computers each) all over the world

- *Many hundreds of machines are involved in a single Google search request* (remember, the web is 400+TB)

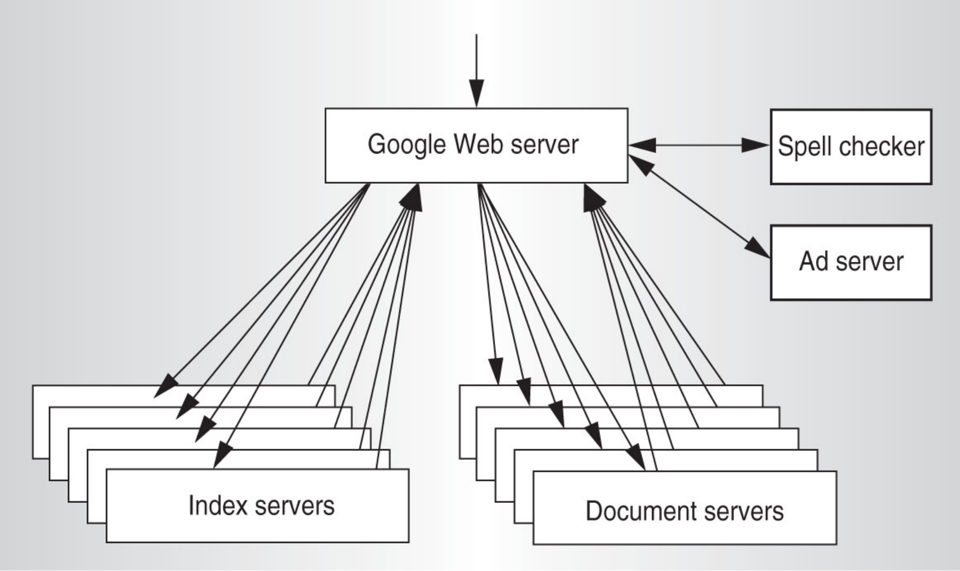
1. DNS routes your search request to a nearby cluster

- A cluster consists of Google Web Servers, Index Servers, Doc Servers, and various other servers (ads, spell checking, etc.)
  - These are cheap standalone computers, rack-mounted, connected by commodity networking gear



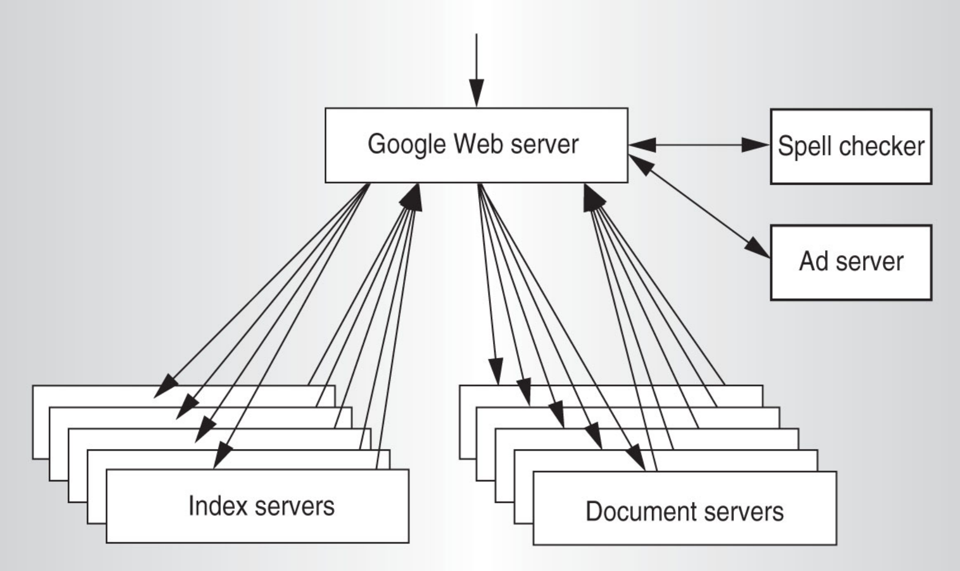


2. Within the cluster, load-balancing routes your search to a lightly-loaded Google Web Server (GWS), which will coordinate the search and response



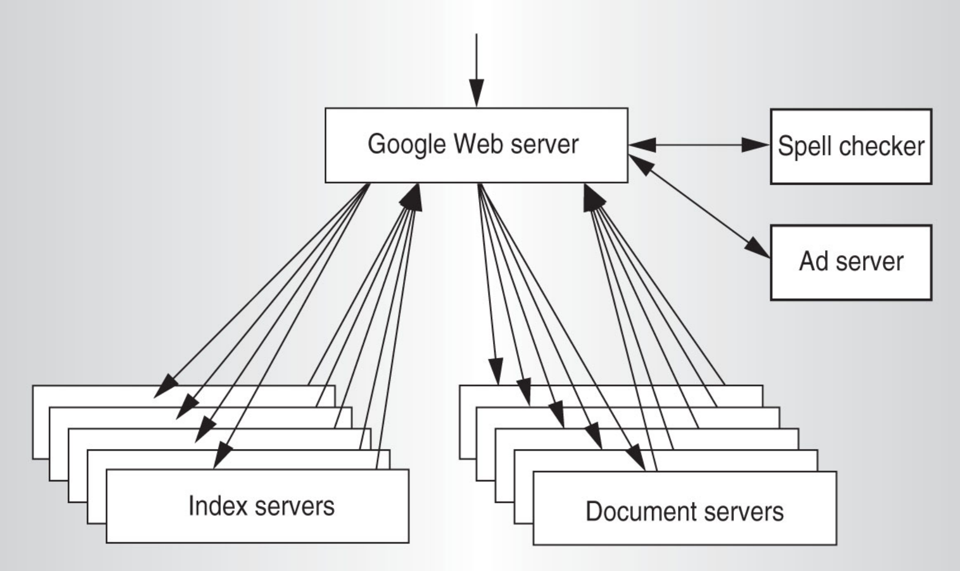
- The index is partitioned into “shards.” Each shard indexes a subset of the docs (web pages). Each shard is replicated, and can be searched by multiple computers – “index servers”

3. The GWS routes your search to one index server associated with each shard, through another load-balancer
4. When the dust has settled, the result is an ID for every doc satisfying your search, rank-ordered by relevance



- The docs, too, are partitioned into “shards” – the partitioning is a hash on the doc ID. Each shard contains the full text of a subset of the docs. Each shard can be searched by multiple computers – “doc servers”

5. The GWS sends appropriate doc IDs to one doc server associated with each relevant shard
6. When the dust has settled, the result is a URL, a title, and a summary for every relevant doc



7. Meanwhile, the ad server has done its thing, the spell checker has done its thing, etc.
8. The GWS builds an HTTP response to your search and ships it off

- Many hundreds of computers have enabled you to search 400+TB of web in ~100 ms.

Google: The Big Picture

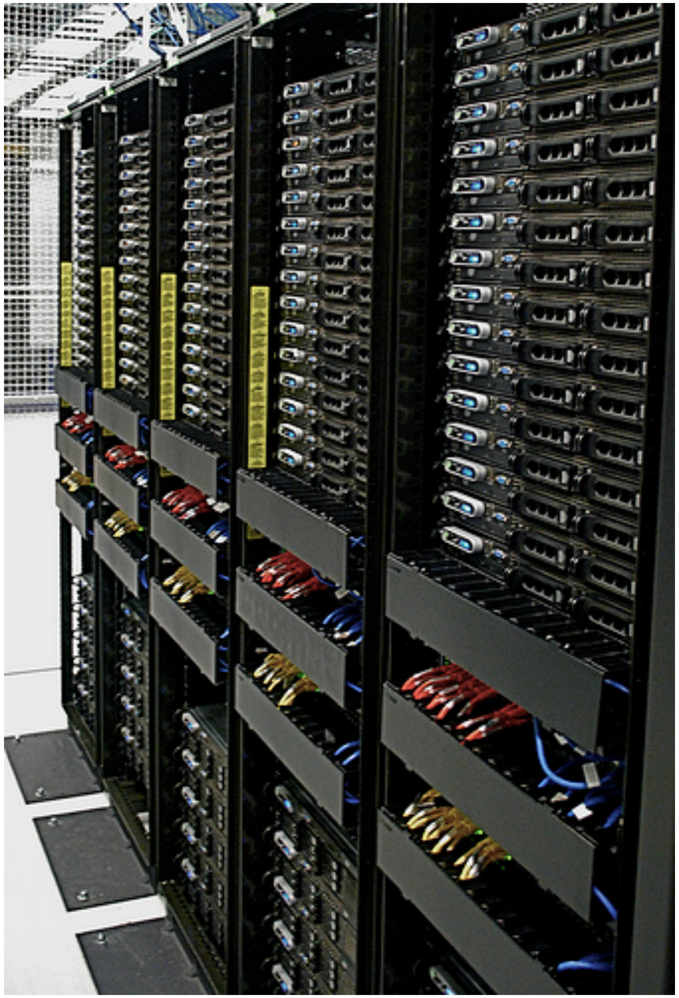
- Enormous volumes of data
- Extreme parallelism
- The cheapest imaginable components
  - Failures occur all the time
  - You couldn't afford to prevent this in hardware
- Software makes it
  - Fault-Tolerant
  - Highly Available
  - Recoverable
  - Consistent
  - Scalable
  - Predictable
  - Secure

How on earth would you enable mere mortals write hairy applications such as this?

- Recognize that many Google applications have the same structure
  - Apply a “map” operation to each logical record in order to compute a set of intermediate key/value pairs
  - Apply a “reduce” operation to all the values that share the same key in order to combine the derived data appropriately
- Build a runtime library that handles all the details, accepting a couple of customization functions from the user – a Map function and a Reduce function
- That’s what MapReduce is
  - Supported by the Google File System and the Chubby lock manager
  - Augmented by the BigTable not-quite-a-database system

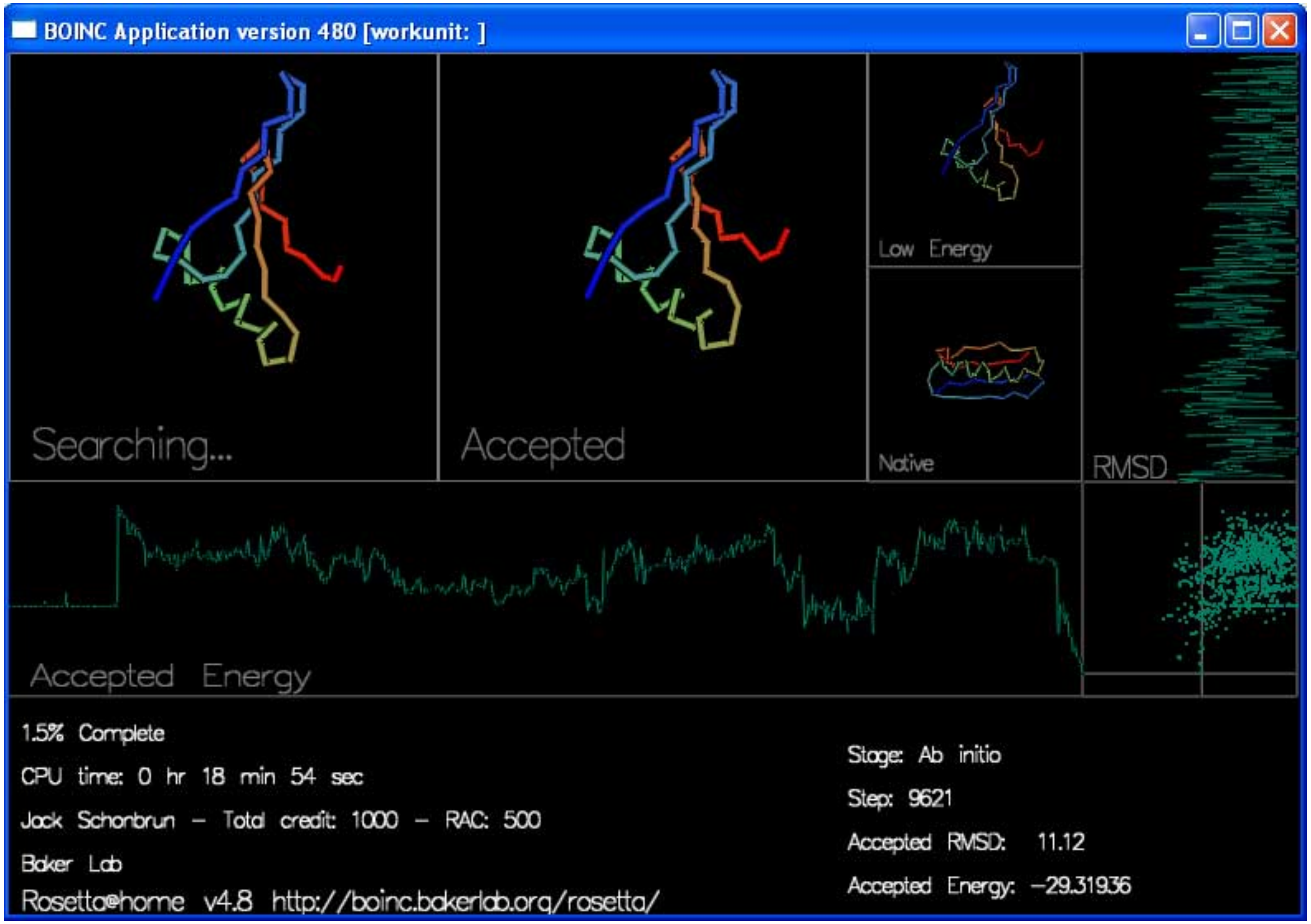
An extremely loosely coupled system: BOINC

David Baker



Rosetta@home

Protein Folding, Design, and Docking

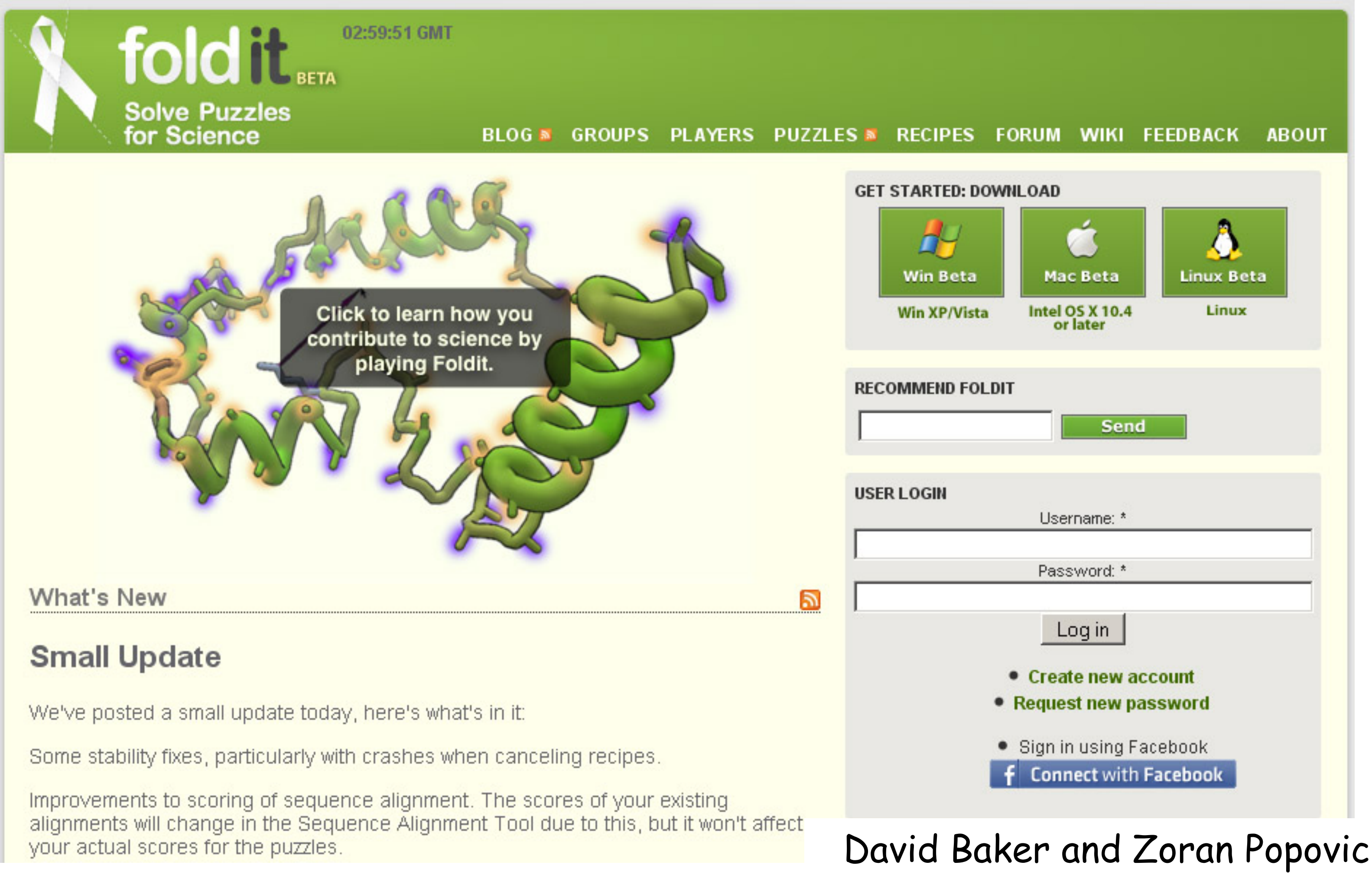


```
1.5% Complete
CPU time: 0 hr 18 min 54 sec
Jack Schonbrun – Total credit: 1000 – RAC: 500
Baker Lab
Rosetta@home v4.8 http://boinc.bakerlab.org/rosetta/

Stage: Ab initio
Step: 9621
Accepted RMSD: 11.12
Accepted Energy: -29.31936
```

Berkeley Open Infrastructure for Network Computing

Totally off the subject of OS: Human Computation



Click to learn how you contribute to science by playing Foldit.

What's New

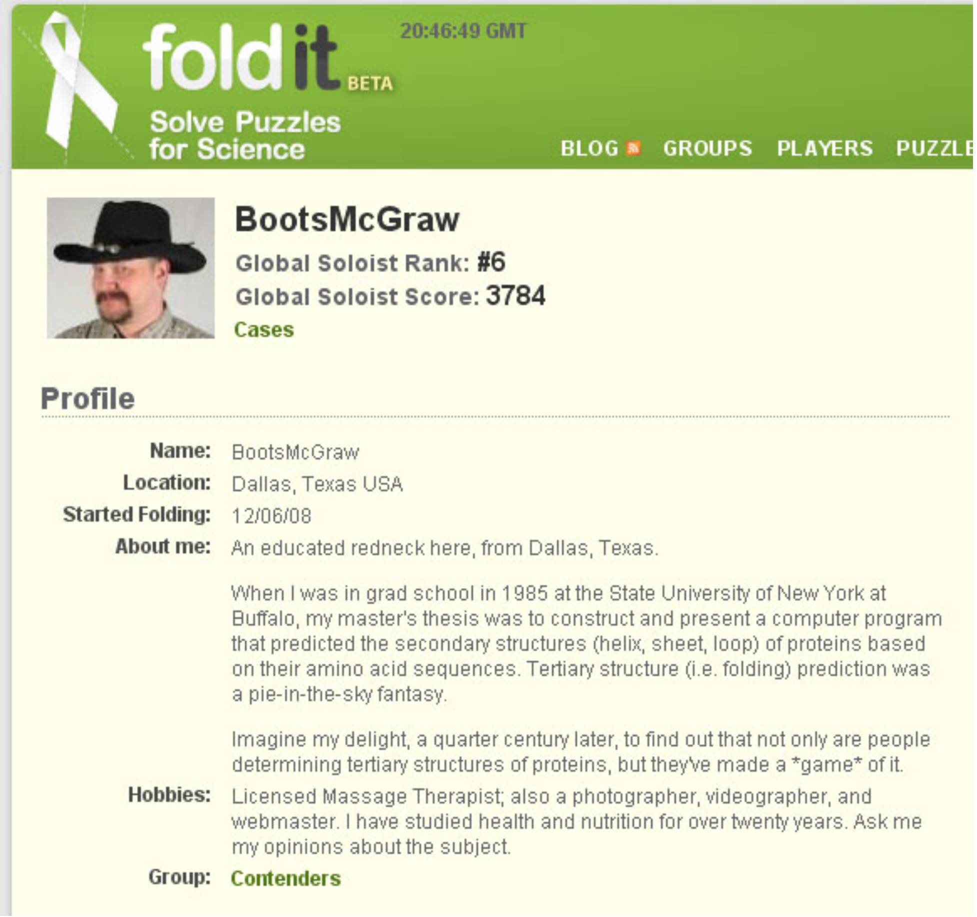
Small Update

We've posted a small update today, here's what's in it:

Some stability fixes, particularly with crashes when canceling recipes.

Improvements to scoring of sequence alignment. The scores of your existing alignments will change in the Sequence Alignment Tool due to this, but it won't affect your actual scores for the puzzles.

David Baker and Zoran Popovic



BootsMcGraw

Global Soloist Rank: #6

Global Soloist Score: 3784

Cases

Profile

Name: BootsMcGraw

Location: Dallas, Texas USA

Started Folding: 12/06/08

About me: An educated redneck here, from Dallas, Texas.

When I was in grad school in 1985 at the State University of New York at Buffalo, my master's thesis was to construct and present a computer program that predicted the secondary structures (helix, sheet, loop) of proteins based on their amino acid sequences. Tertiary structure (i.e. folding) prediction was a pie-in-the-sky fantasy.

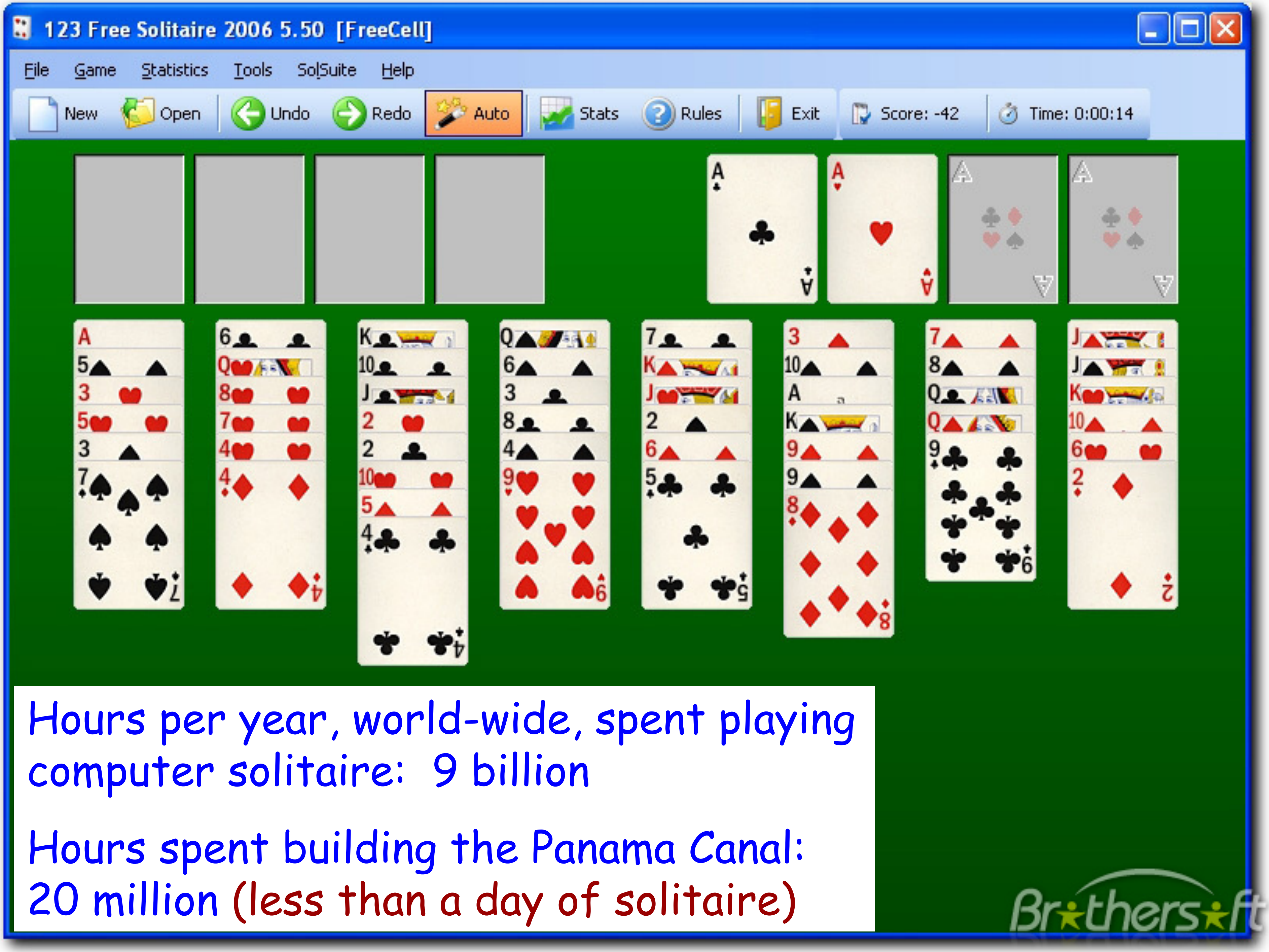
Imagine my delight, a quarter century later, to find out that not only are people determining tertiary structures of proteins, but they've made a *game* of it.

Hobbies: Licensed Massage Therapist; also a photographer, videographer, and webmaster. I have studied health and nutrition for over twenty years. Ask me my opinions about the subject.

Group: Contenders

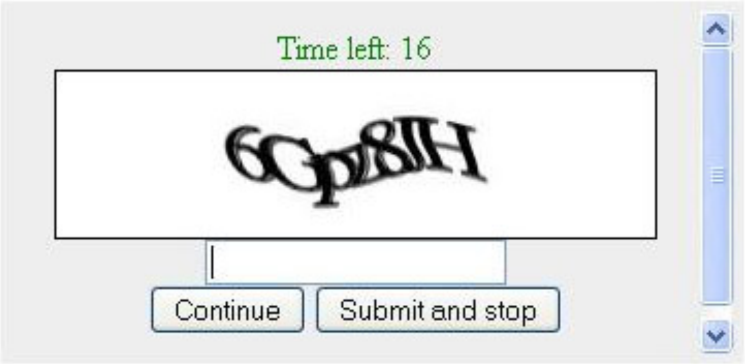
Luis von Ahn

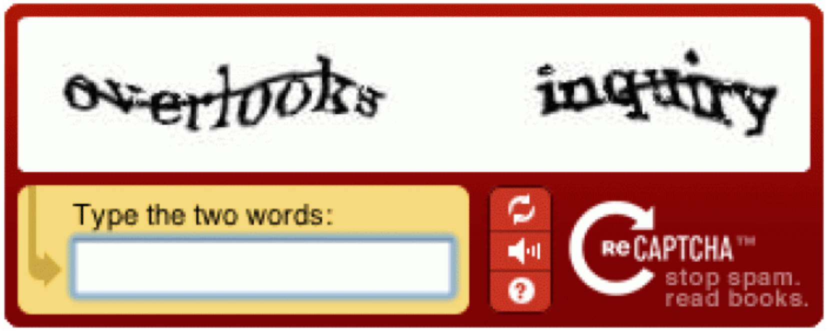
- Humans and computers have different computational strengths
- Can we exploit these differences?
  - To differentiate computers from humans?
    - E.g., to make it harder for spambots to acquire new email accounts from which to send spam
  - To create human/machine computational systems that combine the best of each?


123 Free Solitaire 2006 5.50 [FreeCell]
File Game Statistics Tools SolSuite Help
New Open Undo Redo Auto Stats Rules Exit
Score: -42
Time: 0:00:14
Brothersoft

Hours per year, world-wide, spent playing computer solitaire: 9 billion

Hours spent building the Panama Canal: 20 million (less than a day of solitaire)

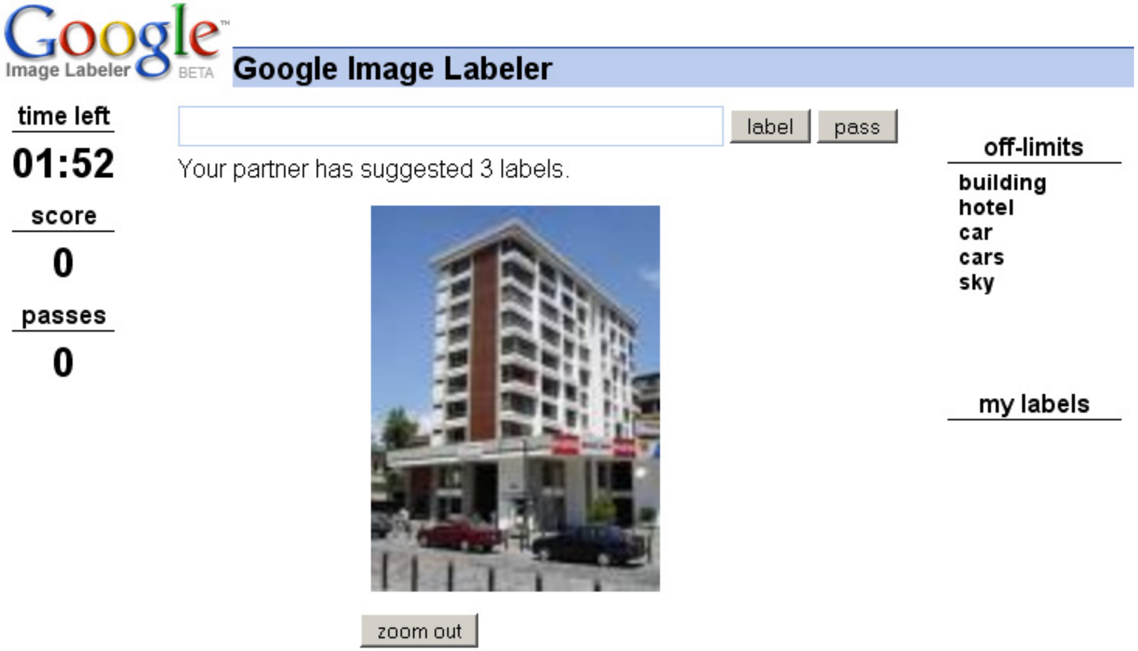

Time left: 16
6Gp8lH
Continue
Submit and stop


overlooks
inquiry
Type the two words:
reCAPTCHA™
stop spam.
read books.

Where do the words come from?

The New York Times

Entire photo archive (years 1851-1980) was completed in 2009



Google Image Labeler

time left
01:52

score
0

passes
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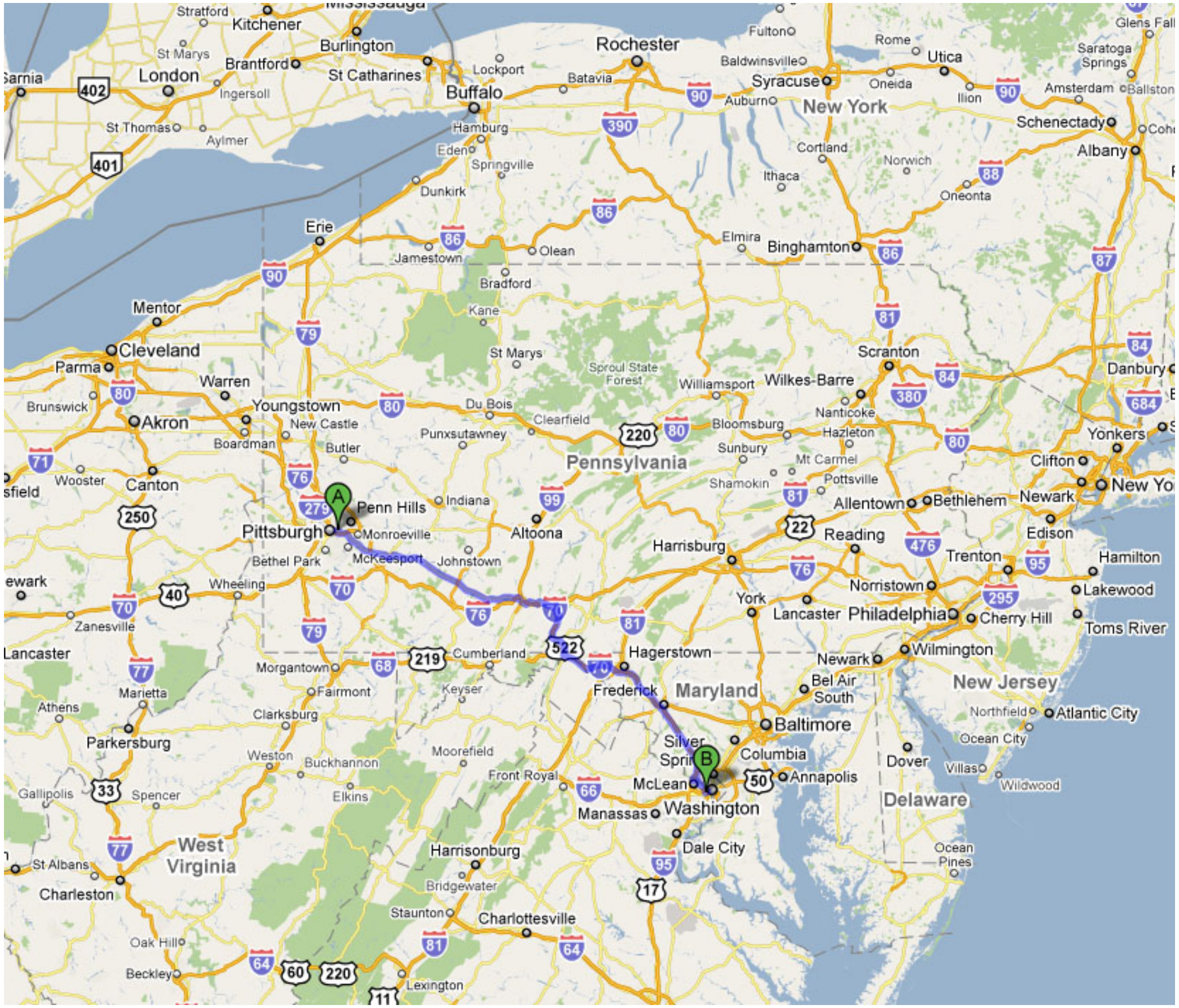
Your partner has suggested 3 labels.

off-limits
building
hotel
car
cars
sky

my labels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B
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Altoona
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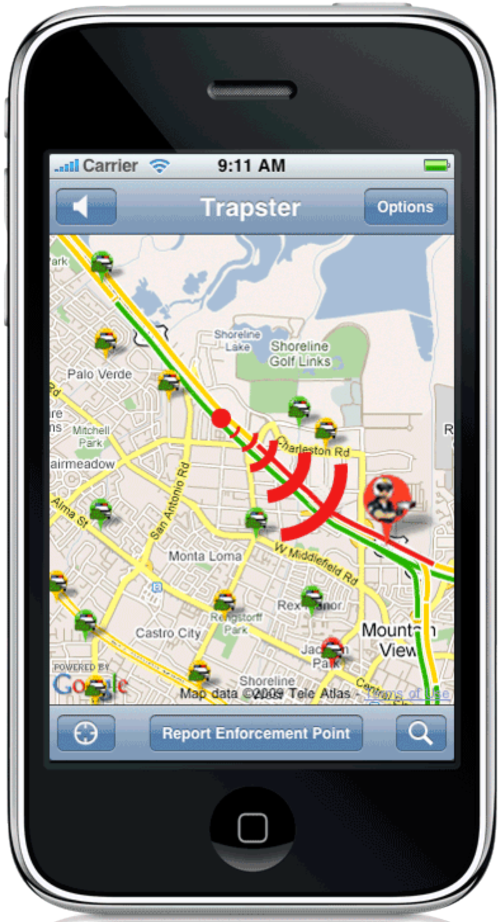
Carrier
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Trapster
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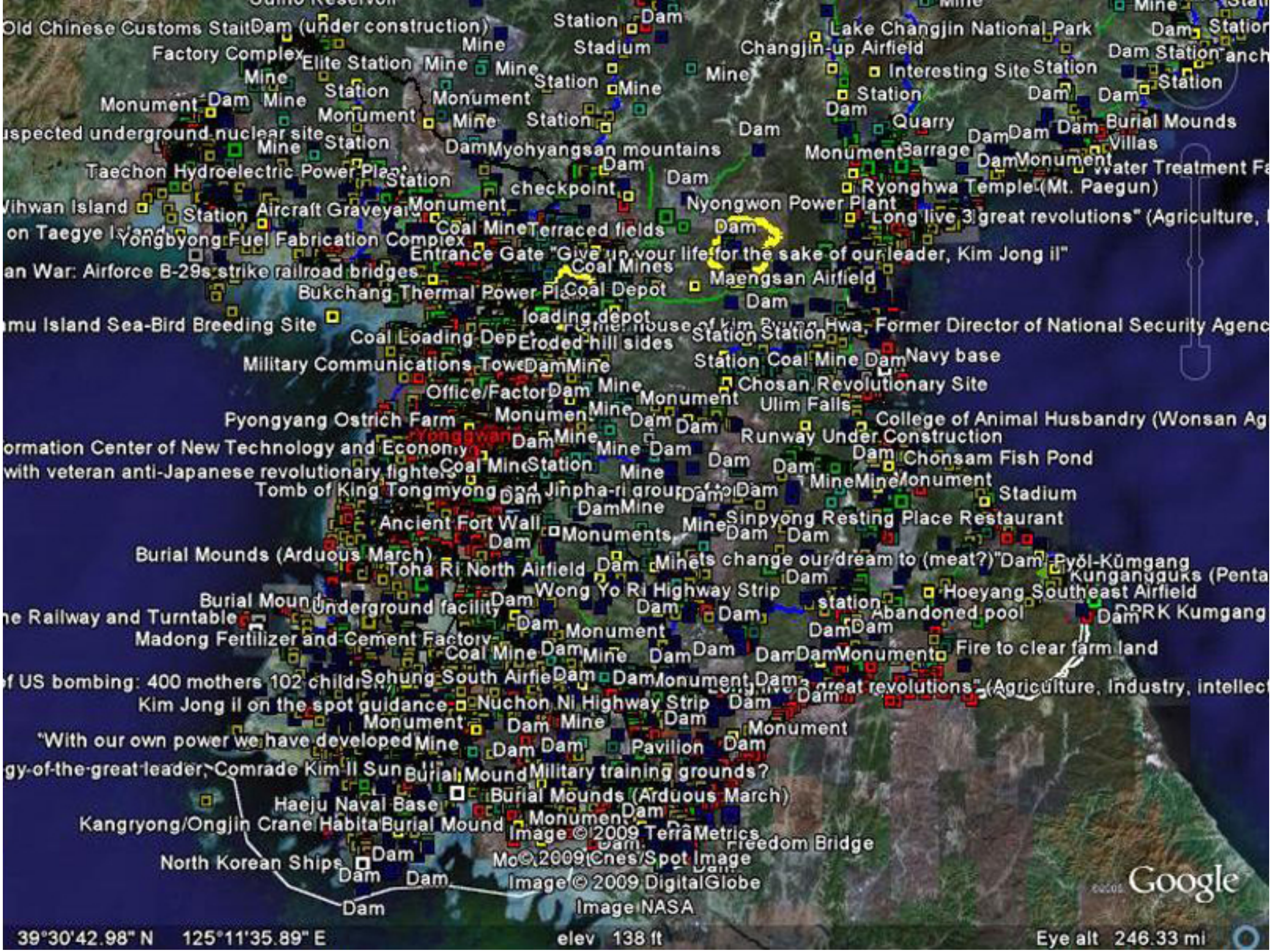
Palo Verde
Shoreline Golf Links
Charleston Rd
Monta Loma
W Middlefield Rd
Castro City
Mountain View
Report Enforcement Point

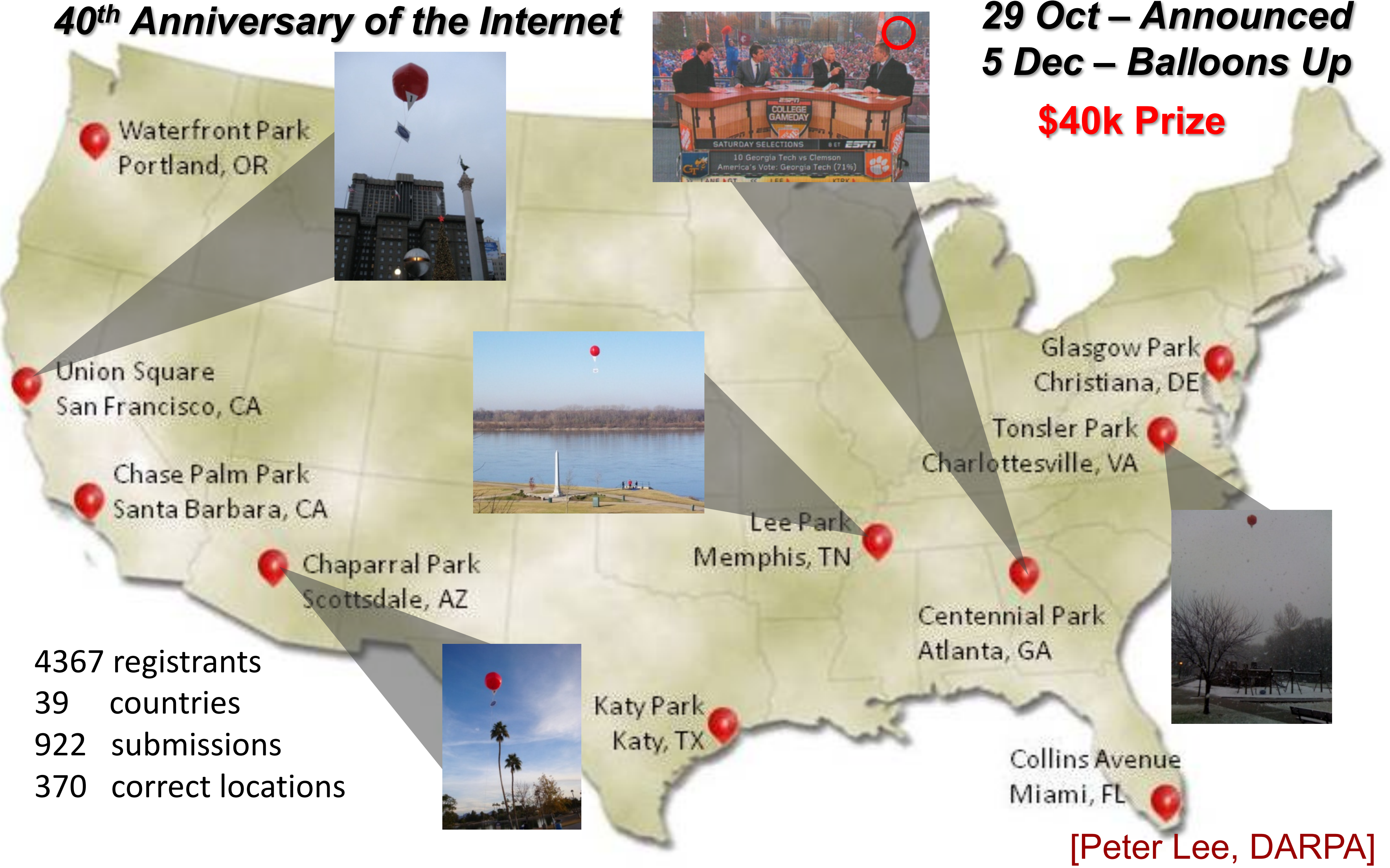

Old Chinese Customs Stait
Dam (under construction)
Station
Dam
Lake Changjin National Park
Dam
Station
Factory Complex
Elite Station
Mine
Stadium
Changjin-up Airfield
Dam Station
Mine
Station
Interesting Site
Station
Monument
Dam
Mine
Monument
Station
Mine
Station
Quarry
Dam
Burial Mounds
uspected underground nuclear site
Mine
Station
Myohyangsan mountains
Monument
Barrage
Villas
Water Treatment Fa
Taechon Hydroelectric Power Plant
checkpoint
Ryonghwa Temple (Mt. Paegun)
Vihwan Island
Aircraft Graveyard
Nyongwon Power Plant
Long live 3 great revolutions" (Agriculture,
on Taegye Island
Yongbyong Fuel Fabrication Complex
Coal Mine
Terraced fields
Entrance Gate "Give up your life for the sake of our leader, Kim Jong il"
an War: Airforce B-29s strike railroad bridges
Coal Mines
Maengsan Airfield
Bukchang Thermal Power Plant
Coal Depot
mu Island Sea-Bird Breeding Site
loading depot
Former house of Kim Byung Hwa, Former Director of National Security Agenc
Coal Loading Depot
Eroded hill sides
Station Station
Military Communications Tower
Coal Mine
Navy base
Office/Factory
Chosan Revolutionary Site
Ulim Falls
Pyongyang Ostrich Farm
College of Animal Husbandry (Wonsan Ag
Yonggwan
Runway Under Construction
ormation Center of New Technology and Economy
Chonsam Fish Pond
with veteran anti-Japanese revolutionary fighters
Coal Mine
Tomb of King Tongmyong and Jinpha-ri group tombs
Stadium
Ancient Fort Wall
Monuments
Sinpyong Resting Place Restaurant
Burial Mounds (Arduous March)
Let's change our dream to (meat?)"
Pyŏl-Kŭmgang
Toha Ri North Airfield
Kunganggukss (Penta
Wong Yo Ri Highway Strip
Hoeyang Southeast Airfield
Burial Mound
Underground facility
station
Abandoned pool
DPRK Kumgang
ne Railway and Turntable
Madong Fertilizer and Cement Factory
Monument
Fire to clear farm land
f US bombing: 400 mothers 102 children
Sohung South Airfield
Long live 3 great revolutions" (Agriculture, Industry, intellec
Kim Jong il on the spot guidance
Nuchon Ni Highway Strip
"With our own power we have developed
Pavilion
gy-of-the-great leader, Comrade Kim Il Sung
Burial Mound
Military training grounds?
Haeju Naval Base
Burial Mounds (Arduous March)
Kangryong/Ongjin Crane Habitat
Burial Mound
Freedom Bridge
North Korean Ships
Image © 2009 TerraMetrics
© 2009 Cnes/Spot Image
Image © 2009 DigitalGlobe
Image NASA
Google
39°30'42.98" N 125°11'35.89" E
elev 138 ft
Eye alt 246.33 mi

DARPA NETWORK CHALLENGE

40th Anniversary of the Internet

29 Oct – Announced
5 Dec – Balloons Up

$40k Prize



4367 registrants
39 countries
922 submissions
370 correct locations

[Peter Lee, DARPA]

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