Algorithms for Cloud Computing

Nokia Wrocław, Poland

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December 29, 2015

Miotacze Piorunów Team :-)

Miotacze Piorunów - the flag :-)

Roadmap

http://dailynewsdig.com/wp-content/uploads/2013/06/20-Funny-Shocked-Cat-Memes-3.jpg

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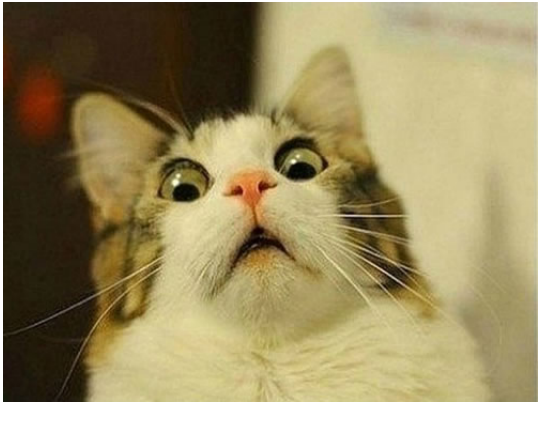

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Cloud blitzkrieg! :-)

http://upload.wikimedia.org/wikipedia/commons/1/10/Bundesarchiv_Bild_101I-646-5188-17%2C_Flugzeuge_Junkers_Ju_87.jpg

Part 1

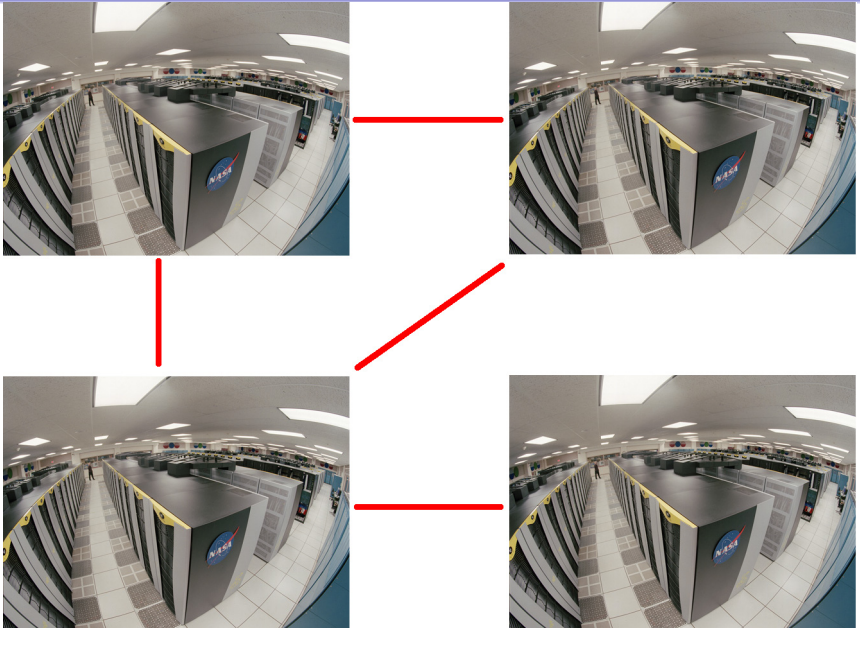
Supercomputers - ’60-’80

http://upload.wikimedia.org/wikipedia/commons/c/c4/CDC_6600.jc.jpg

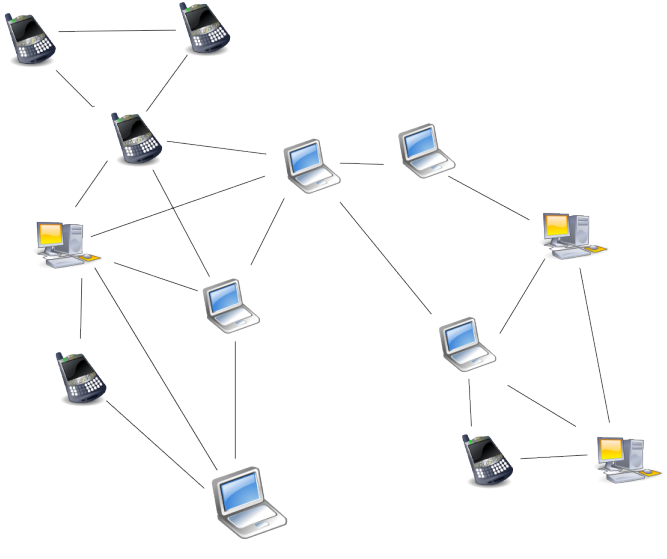
Clusters - since ’70

http://upload.wikimedia.org/wikipedia/commons/3/3d/Us-nasa-columbia.jpg

Grids - since ’90



P2P - since end of ’90



http://upload.wikimedia.org/wikipedia/en/f/fa/Unstructured_peer-to-peer_network_diagram.png

Clouds - since ’00

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- No single definition
  - A bit grid-like
  - With massive storage
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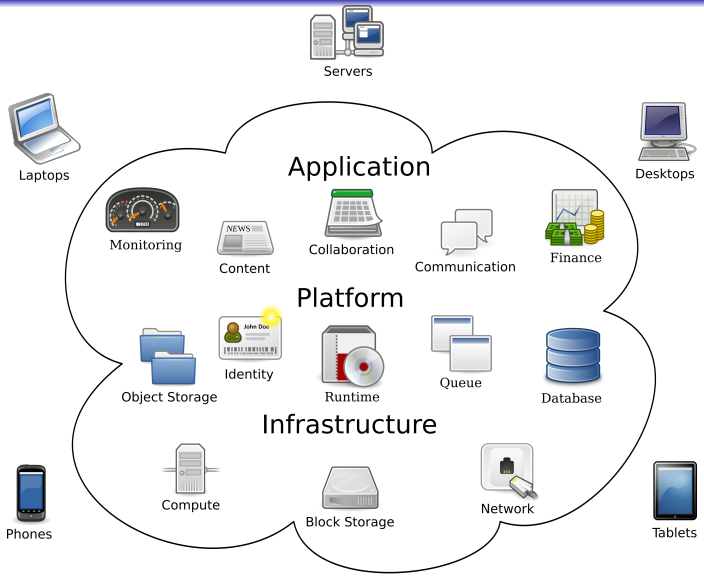
  - **S C A L E!**

Cloud types



http://upload.wikimedia.org/wikipedia/commons/b/b5/Cloud_computing.svg

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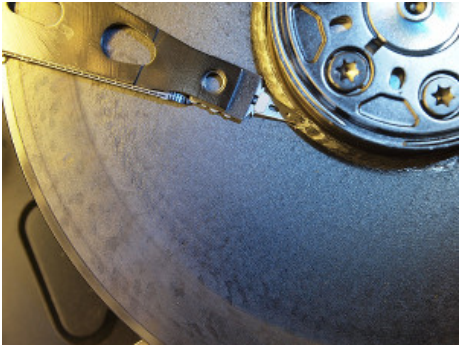

Lesson learned

At scale incredibly rare is a commonplace.

http://upload.wikimedia.org/wikipedia/commons/b/b9/Hard_disk_failure.jpeg

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  - Any time
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  - . . .
- Addressed by software
- Algorithms

http://upload.wikimedia.org/wikipedia/commons/1/19/Train_wreck_at_Montparnasse_1895.jpg

Part 2

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- Node has new data
- How to inform others?

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- We can do better than that...

The solution

1. Each node:
    1. Pick random node
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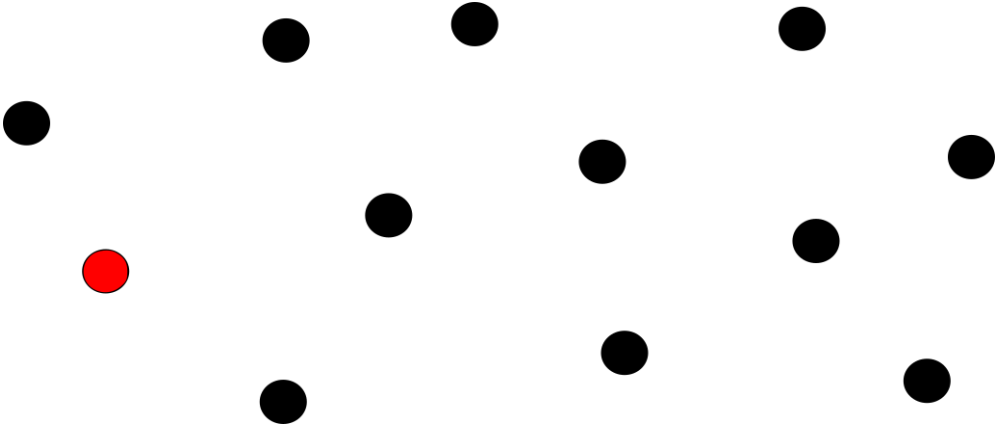

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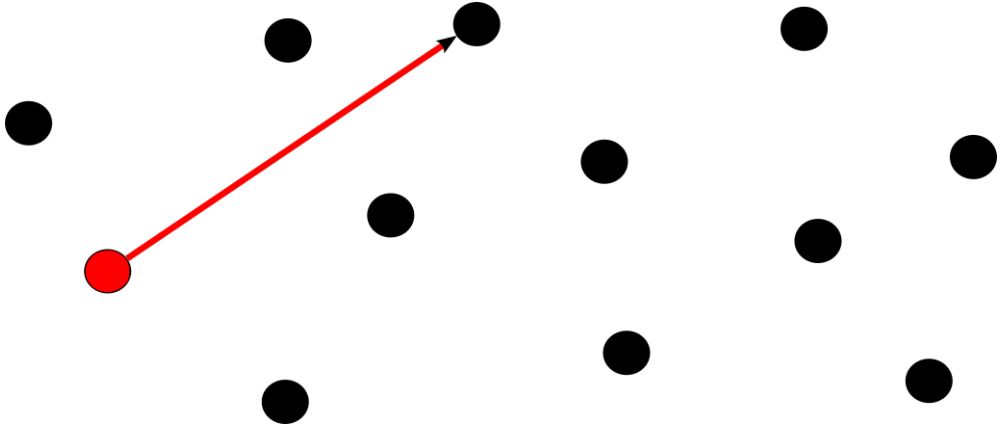

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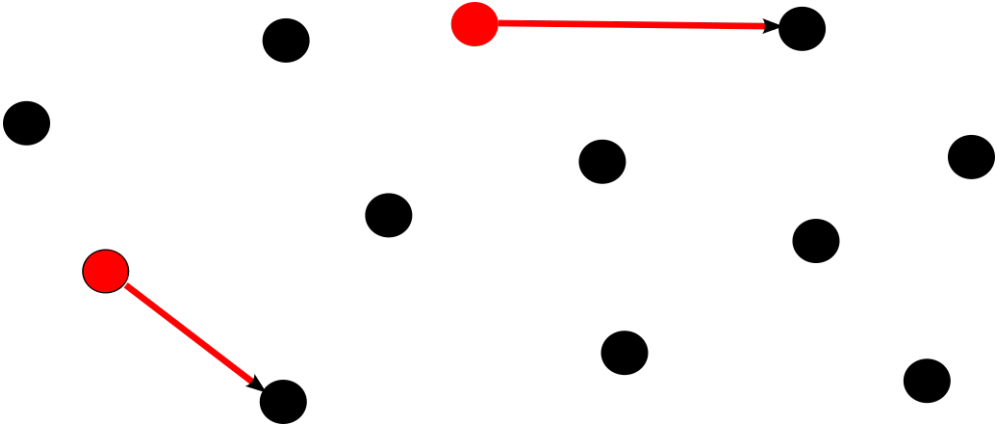

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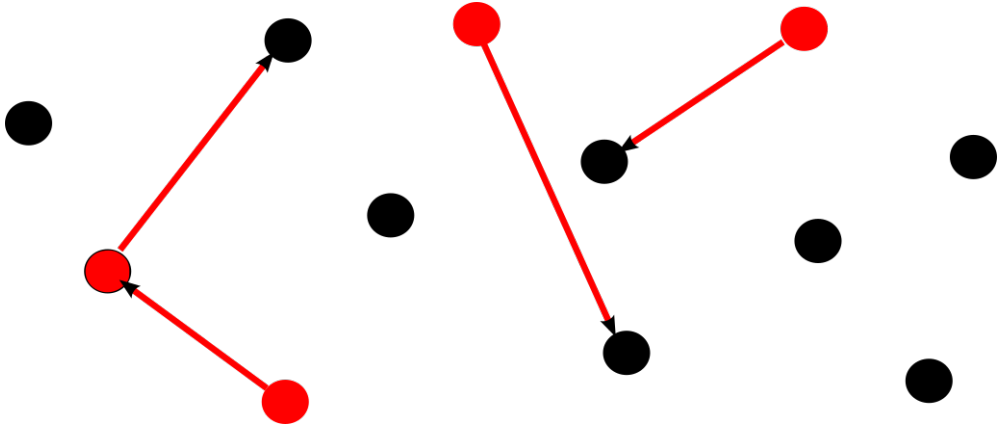

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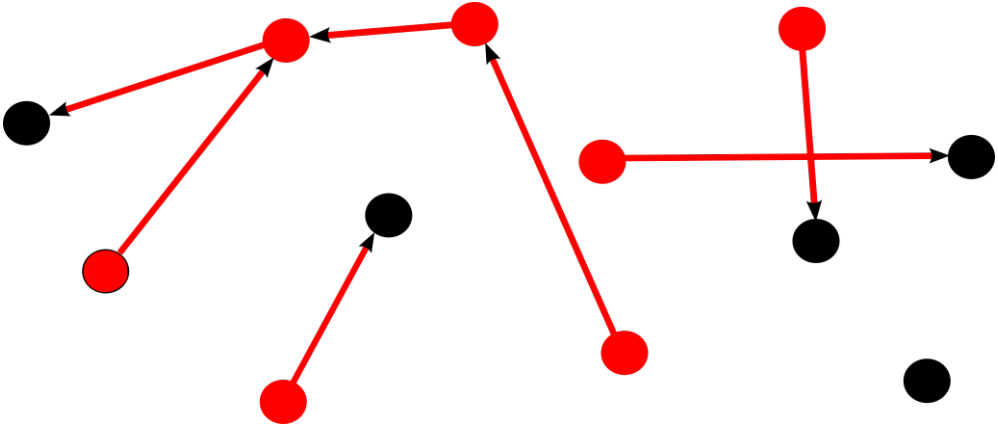
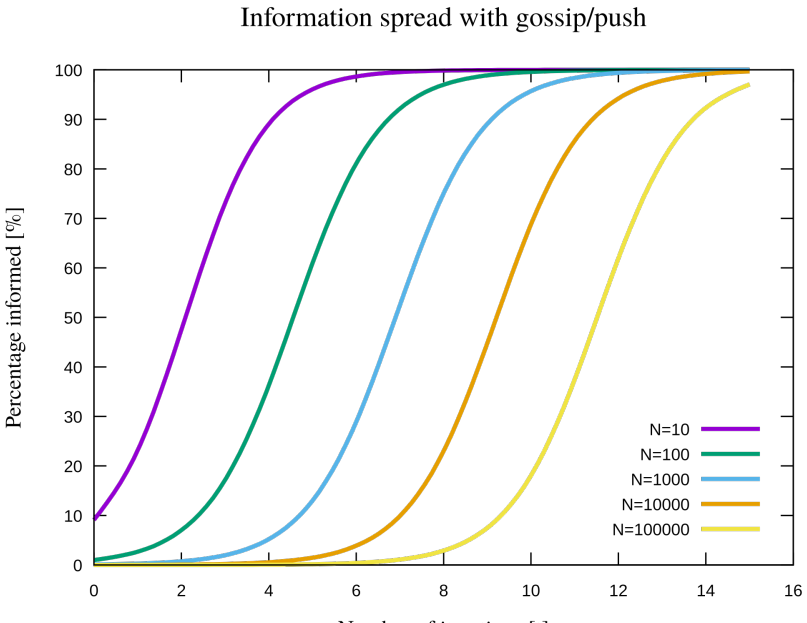


Spreads like a disease!



Gossip at Amazon S3

- Amazon S3:
  - **S**imple **S**torage **S**ervice
  - Online file storage
  - Part of *Amazon Web Services*
- Gossiping:
  - Spreading state info
  - Base component of storage
- Some numbers:
  - Over $2 * 10^{12}$ objects (2013)
  - 99.9% availability/month
  - 99.99% availability/year
  - 99.999999999% durability/year

https://upload.wikimedia.org/wikipedia/commons/e/ed/AWS_Simple_Icons_Storage_Amazon_S3_Bucket_with_Objects.svg
https://upload.wikimedia.org/wikipedia/commons/1/1d/AmazonWebservices_Logo.svg

Part 3

Basic concepts

- Aka. "failure detection"

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  - *Speed* == time to first detection
  - *Scale* == distributing load on nodes uniformly
- **Accuracy** vs. **completeness**
- Cannot have both (over unreliable networks)!

The idea

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- Sounds familiar? :-)

Yup!

Local entries table

- Each node keeps table
- Table for node **A**:

1	2	3
A	5	
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  3. Entry timeout
- Timeout is local
- Timed out entries are dead
- Heartbeat incremented on send

Merging entries

A

A	5	
B	4	-41
C	5	-13

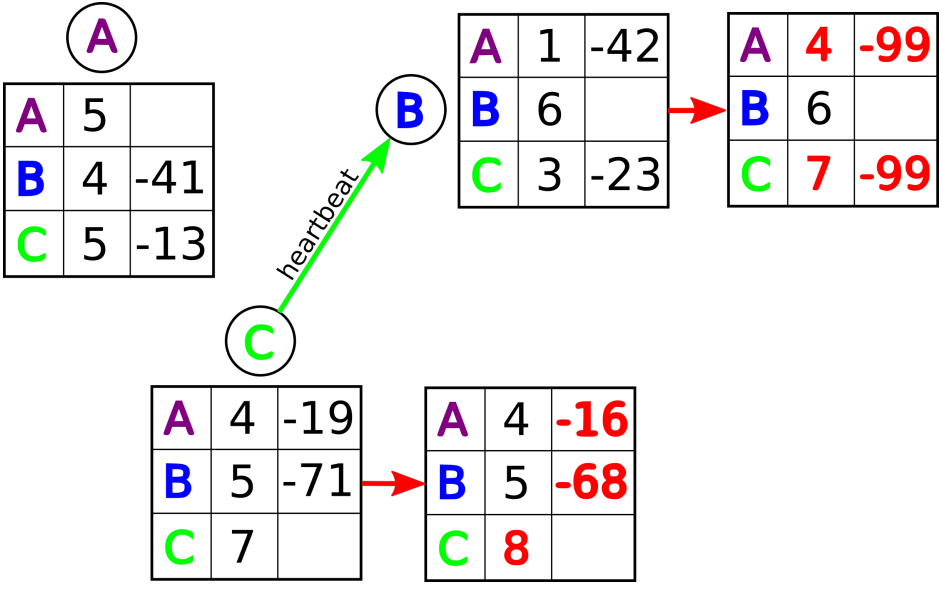
B

A	1	-42
B	6	
C	3	-23

C

A	4	-19
B	5	-71
C	7	

Merging entries



Amazon DynamoDB

- Amazon DynamoDB:
  - Database-like
  - Distributed Hash Table (DHT)
  - Powers Amazon Web Services
  - Used by Amazon S3
- Membership + failure detection
- No central register
- Excellent scaling

https://upload.wikimedia.org/wikipedia/commons/e/ed/AWS_Simple_Icons_Storage_Amazon_S3_Bucket_with_Objects.svg
https://upload.wikimedia.org/wikipedia/commons/1/1d/AmazonWebservices_Logo.svg

Part 4

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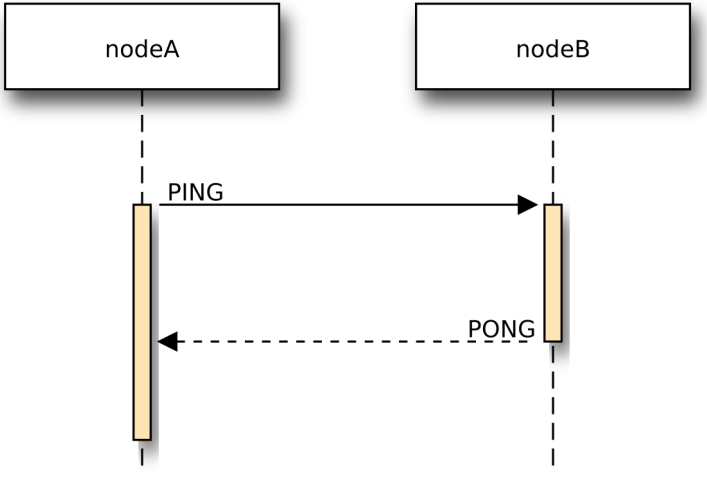
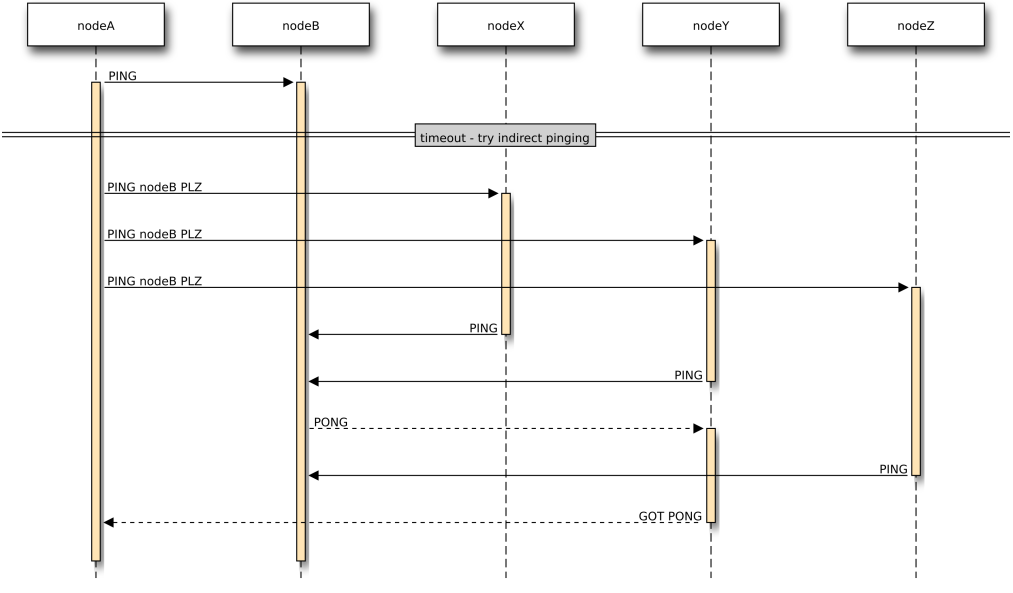
- Extra attempt to verify:
  - Special (more network paths)
  - Temporal (more time to response)

Example - direct ping succeeded

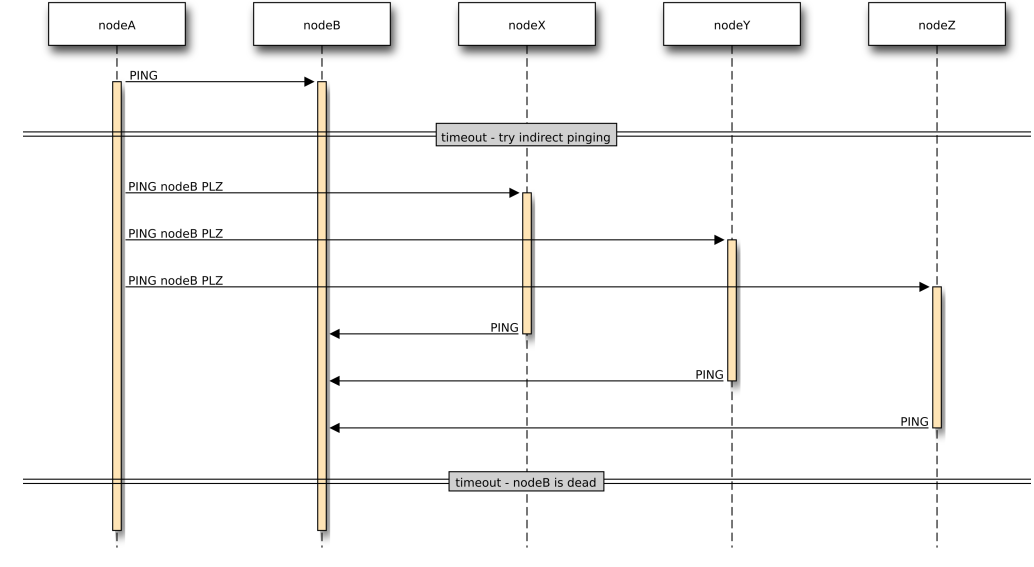
Example - direct ping succeeded



Example - direct ping failed



Example - all pings failed



Suspicion mechanism

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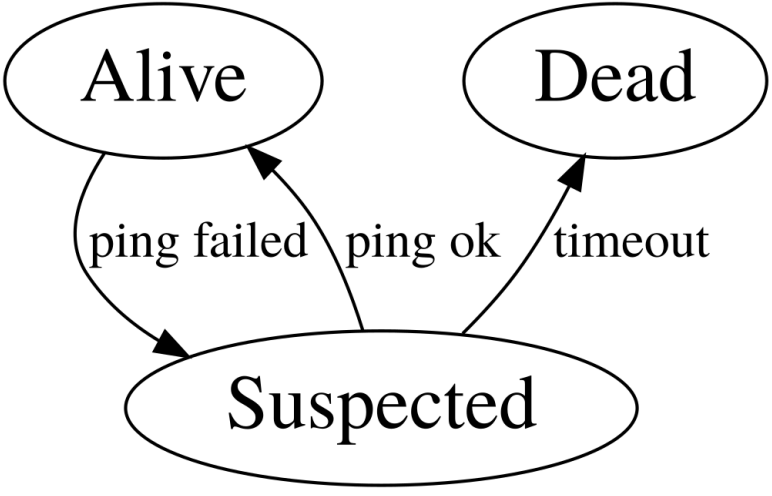

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  - Output: (key -> merged-values)

Cars example

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  - 1991:
    - Opel Vectra, ABS
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- Query: which cars where produced when?
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  - Dodge Viper: 1992-1995
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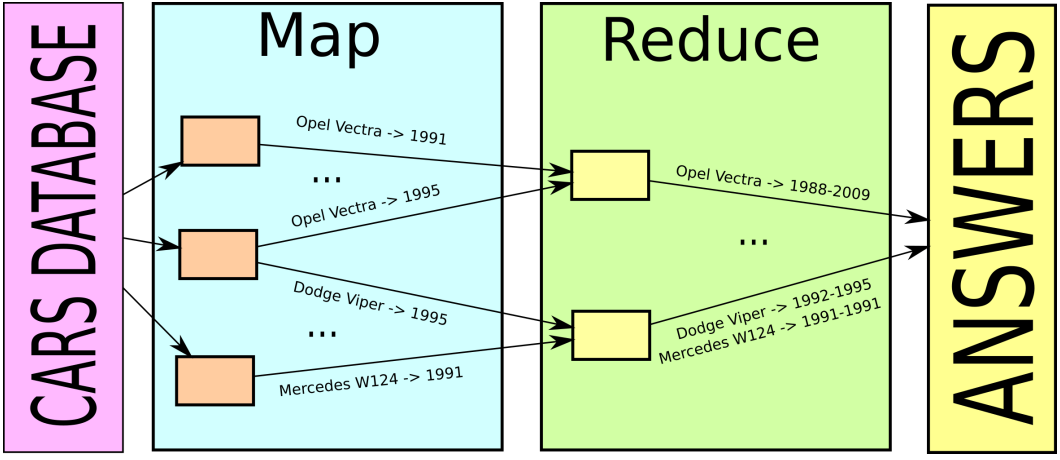
Computations



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- Reducing:
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- Algorithm:
  - Highly parallel
  - Widely adopted
  - Common solution for batch tasks

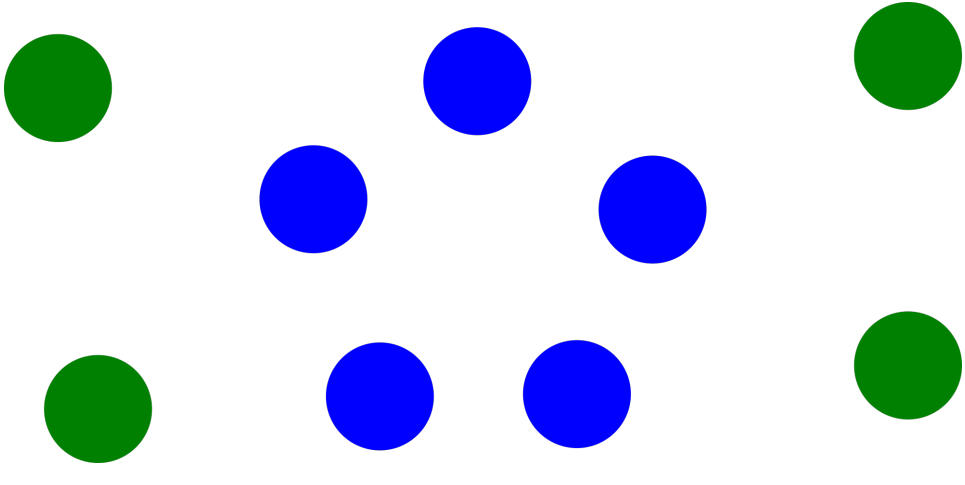
Practical applications

https://upload.wikimedia.org/wikipedia/commons/a/aa/Logo_Google_2013_Official.svg
https://upload.wikimedia.org/wikipedia/commons/0/0e/Hadoop_logo.svg
https://upload.wikimedia.org/wikipedia/en/f/f8/CouchDB.svg

https://upload.wikimedia.org/wikipedia/en/e/eb/MongoDB_Logo.png
https://upload.wikimedia.org/wikipedia/en/8/8e/Riak_distributed_NoSQL_key-value_data_store_logo.png

Part 6

Once upon a time...



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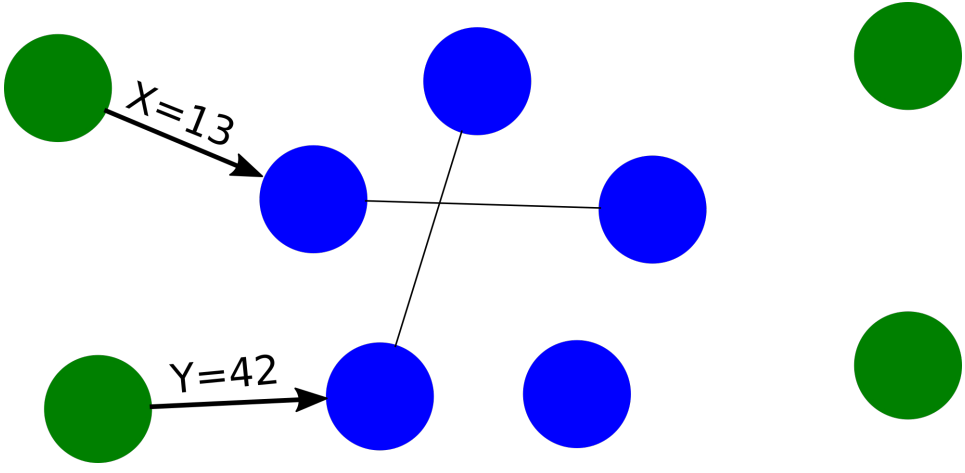

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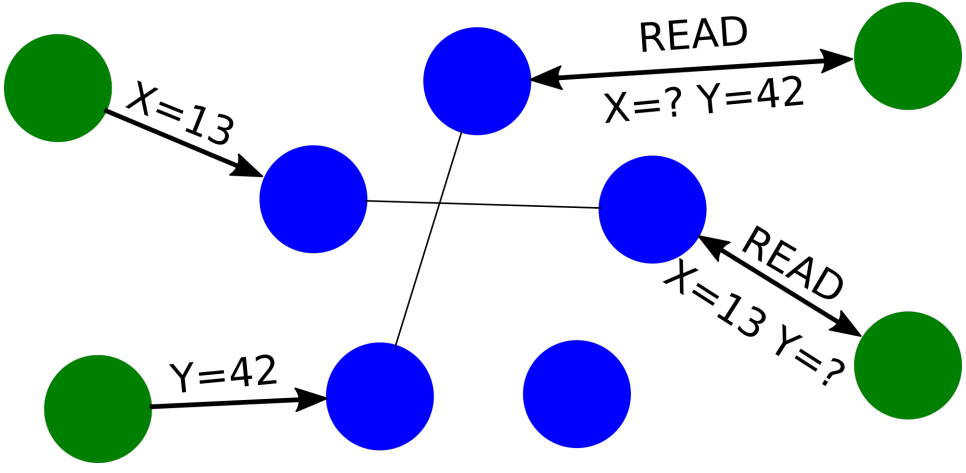

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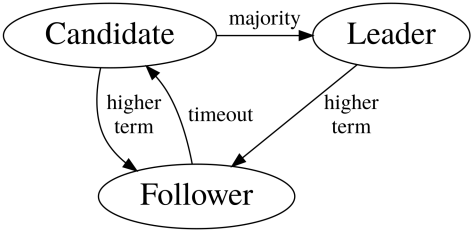
- Example algorithms:
  - Paxos
  - Raft

Raft's organization

- Node is in a given state



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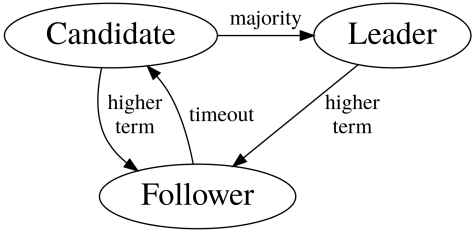

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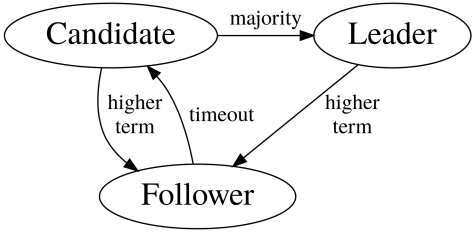

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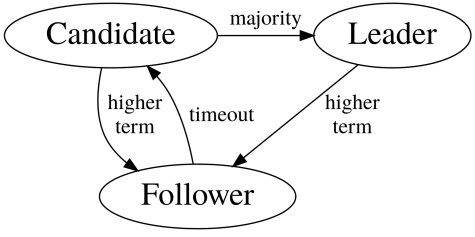
- Leader:
  - Send heartbeats
  - Synchronizes followers
- Clients talk with leader

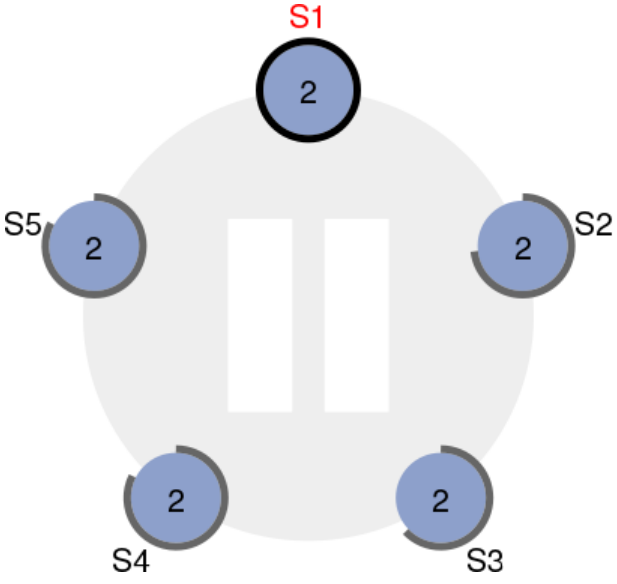


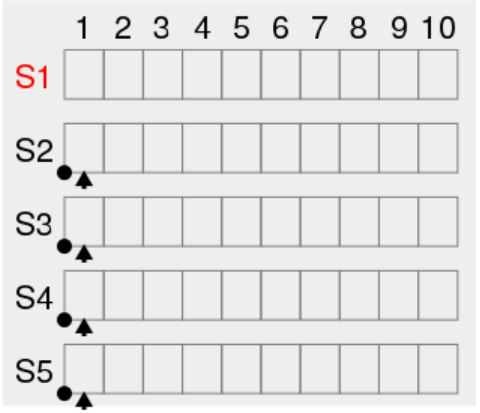
Log replication

https://fiftytwomedia.files.wordpress.com/2011/05/cloned-sheep.jpg

How log (state machine) is replicated?

Log replication





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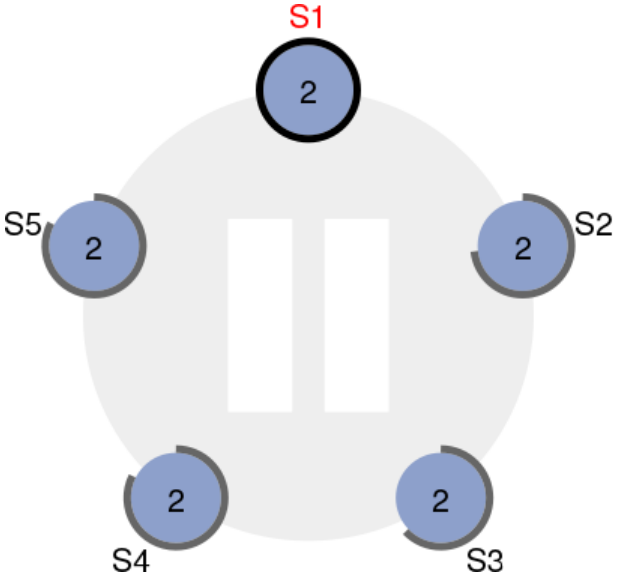

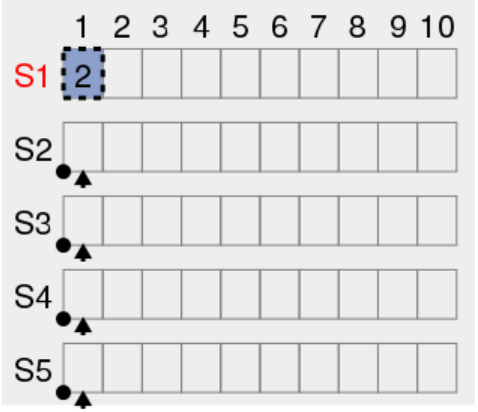

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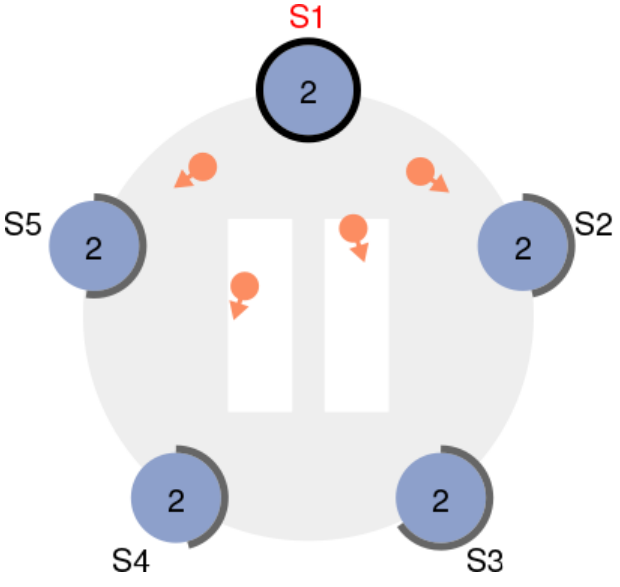
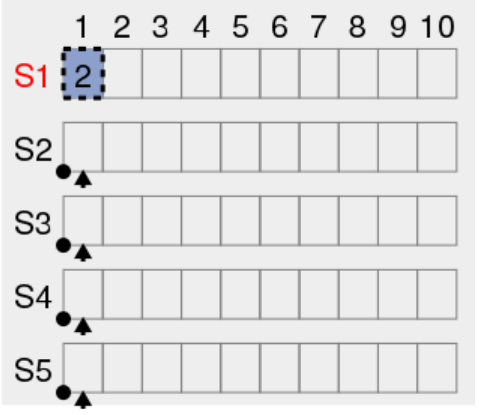
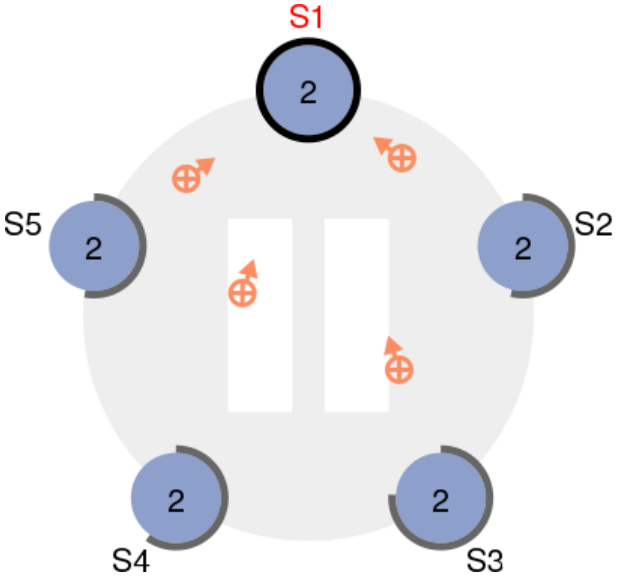
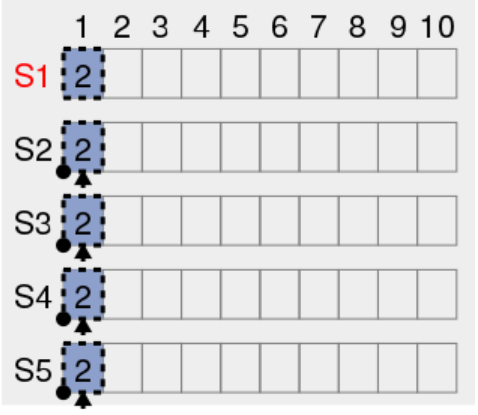


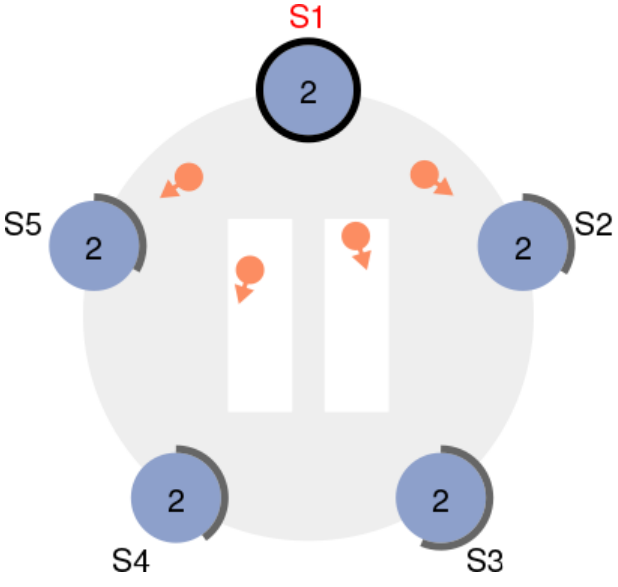


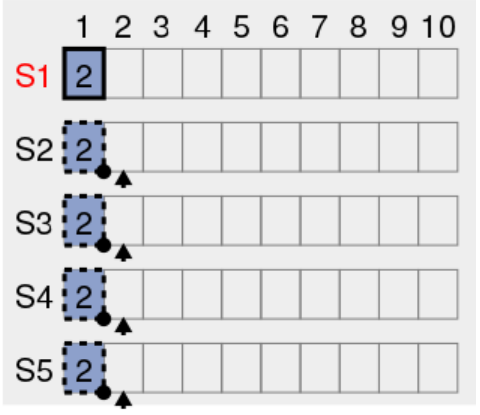
Log replication



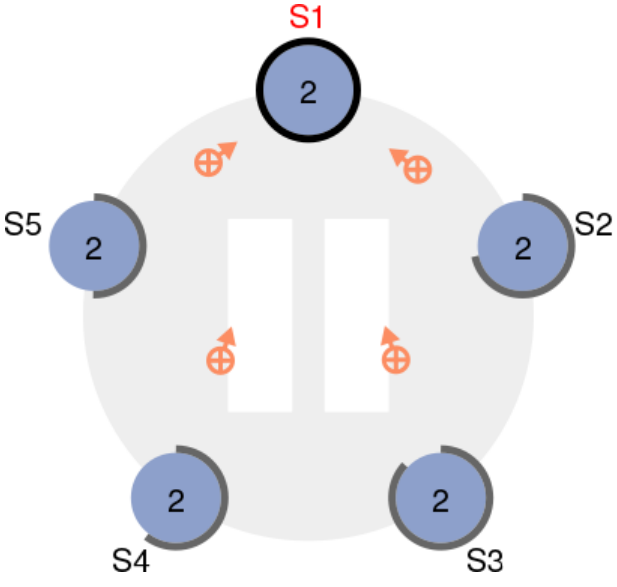


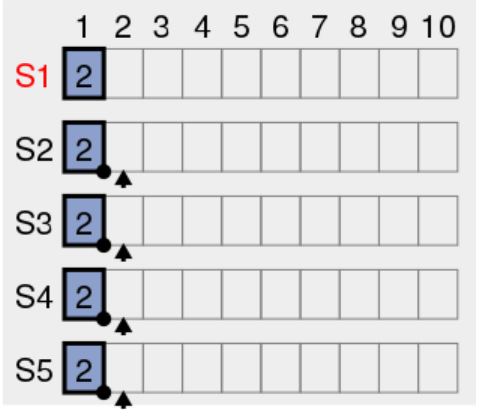
Log replication





Log replication



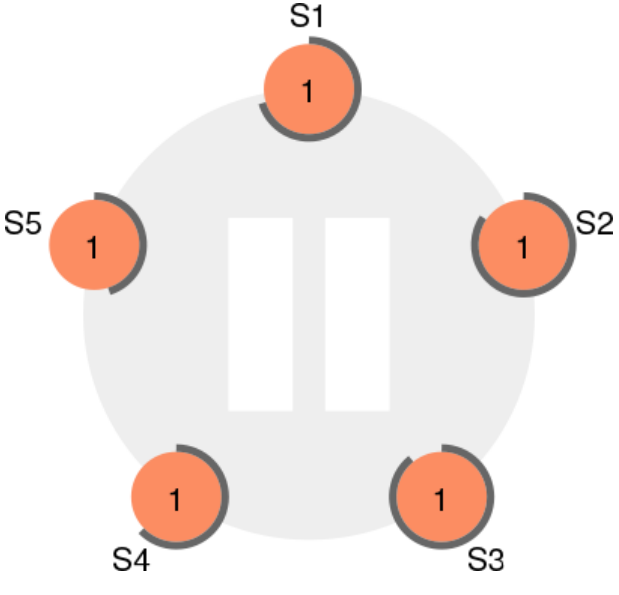


Leader election

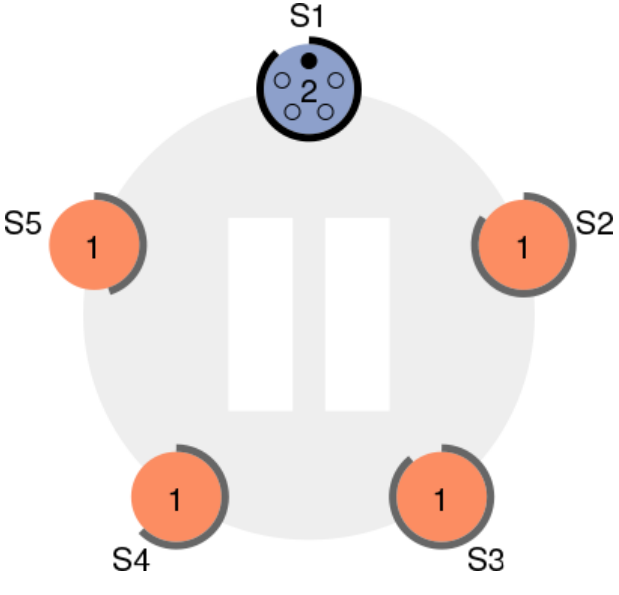
How leader election works?

http://i.huffpost.com/gen/1849024/thumbs/o-ELECTION-BALLOT-facebook.jpg

Leader election



Leader election



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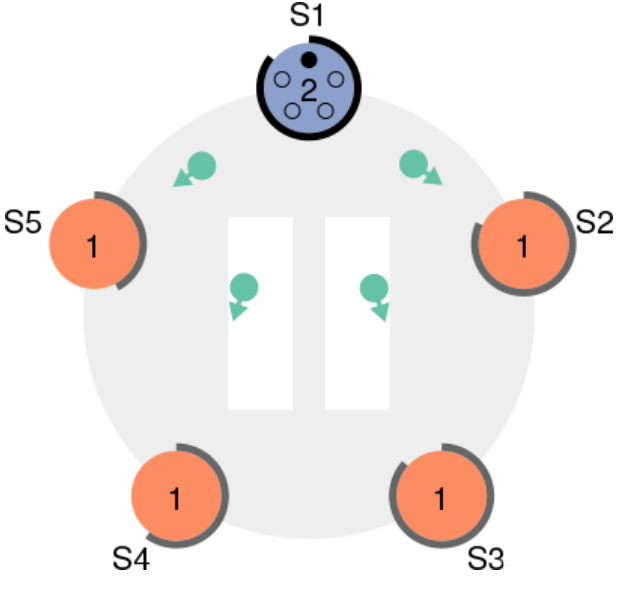
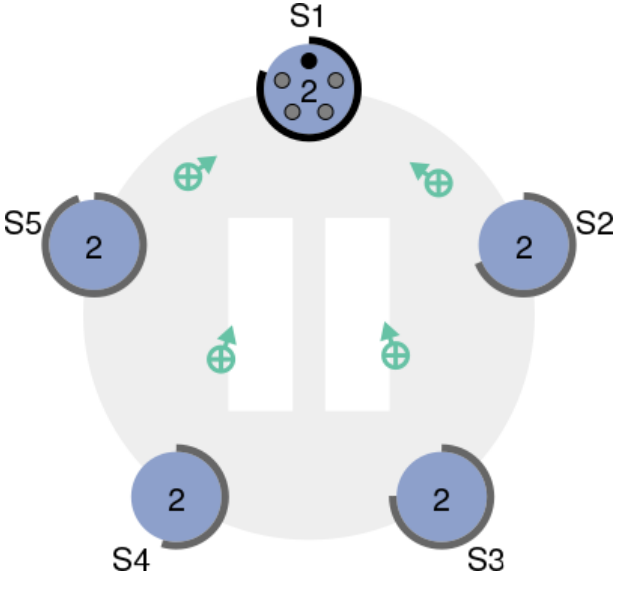
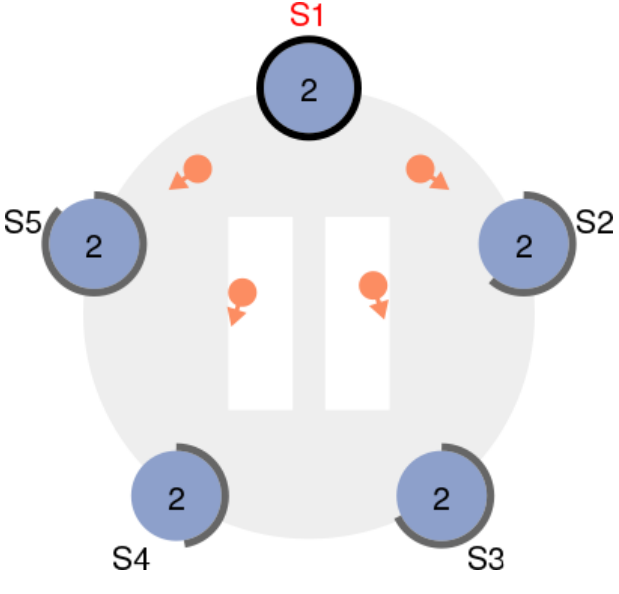


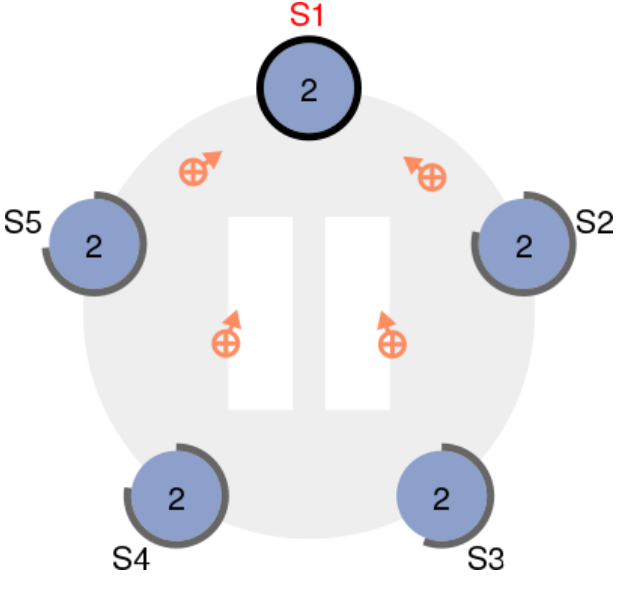
Leader election



Leader election



Leader election

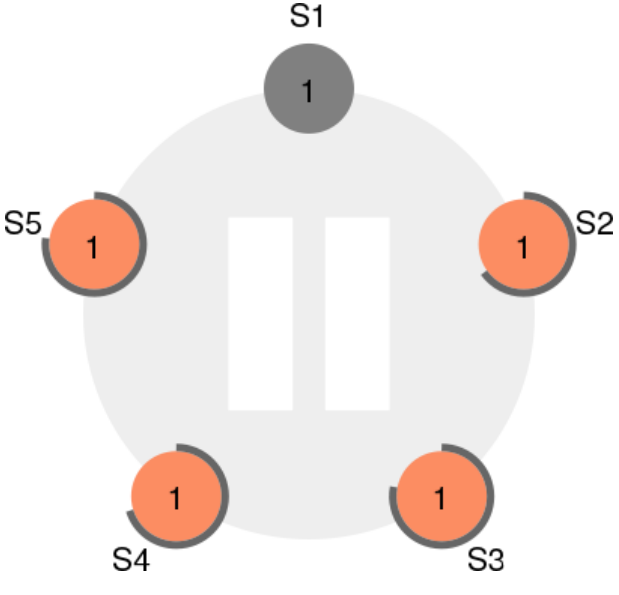


That simple?

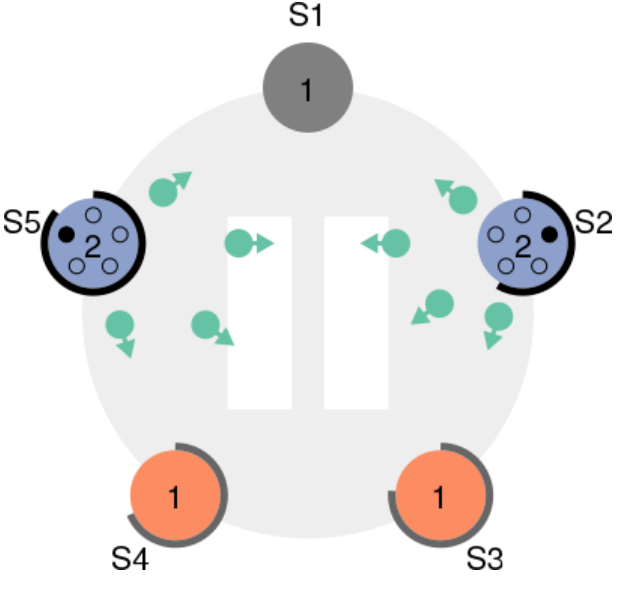
http://cache.gawkerassets.com/assets/images/4/2010/01/500x_hamshred.jpg

Does leader election always work?

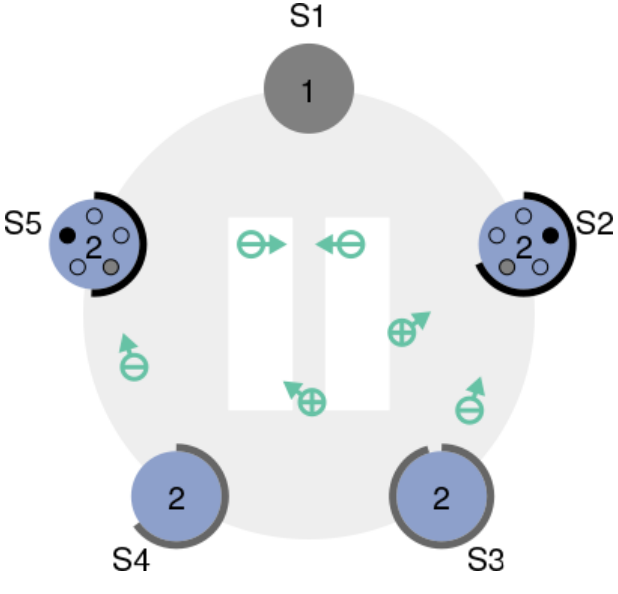
Split vote



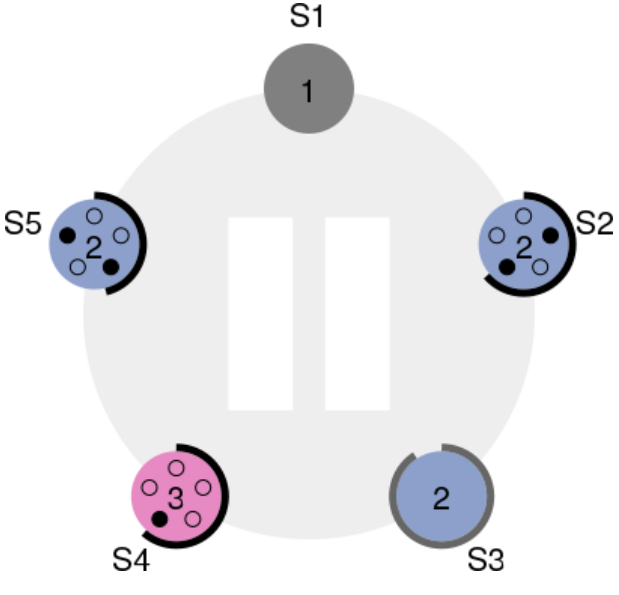
Split vote



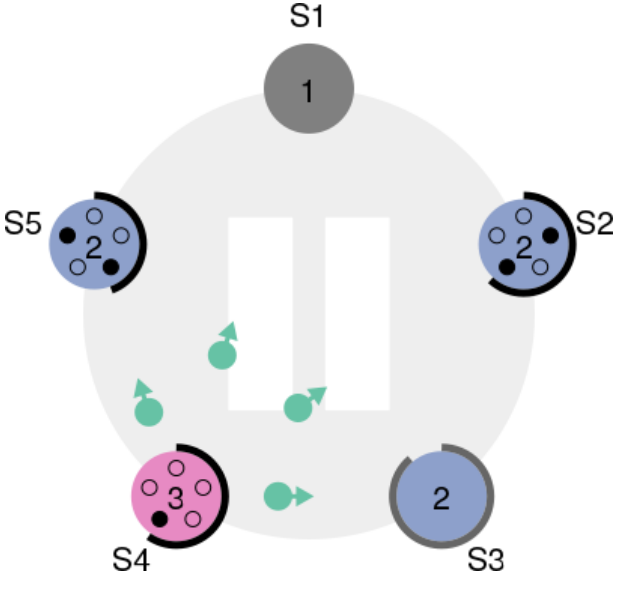
Split vote



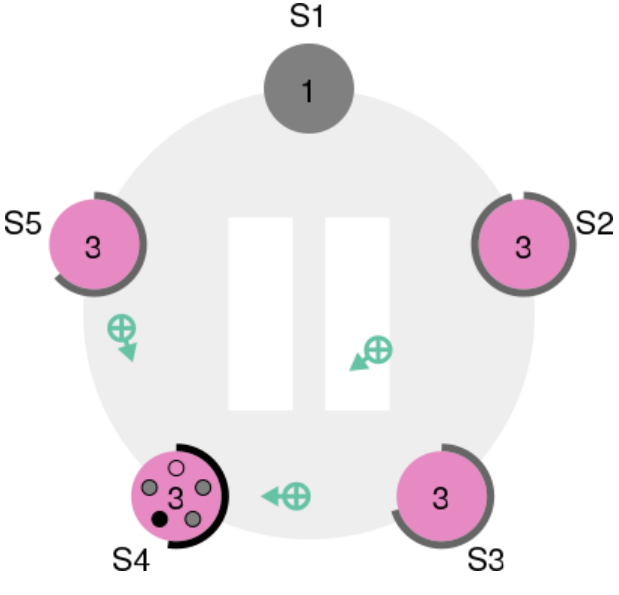
Split vote



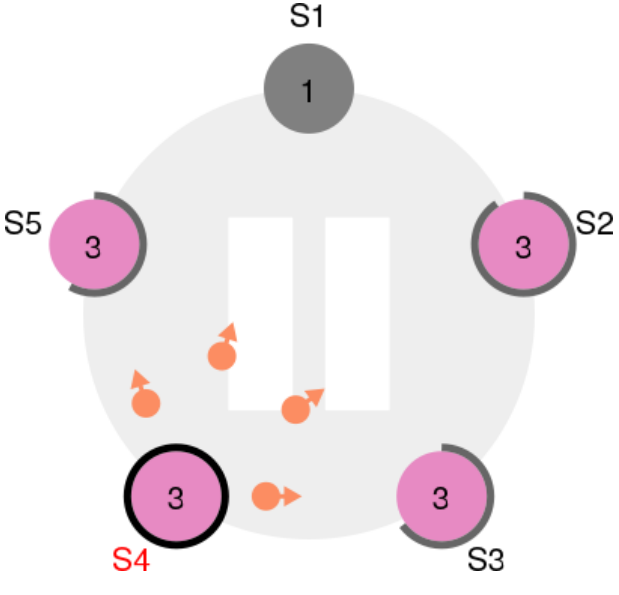
Split vote



Split vote



Split vote



Raft's ecosystem

- Base of CockroachDB

- Widespread use
- "Paxos made simple"

Raft's ecosystem

- Base of CockroachDB

- Widespread use
- "Paxos made simple"

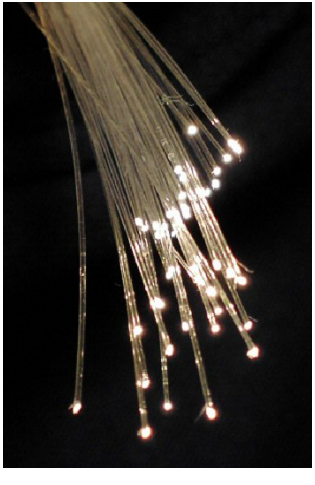
Raft's implementations:

cppa-raft, LogCabin, bspolley/raft, noeleo/raft, whitewater, willemt/raft, NRaft, dupdob/RAFTiNG, dinghy, melee, raft-clj, rodriguezvalencia/rafting, draft, zraft_lib, eraft, huckleberry, rafter, rafterl, Flotten, graft, go-raft, etcd/raft, hashicorp/raft, jpathy/raft, peterbourgon/raft, pontoon, seaturtles, kontiki, allengeorge/libraft, barge, chicm/CmRaft, copycat, drpicox/uoc-raft-2013p, jalvaro/raft, jgroups-raft, RaftKVDatabase/JSimpleDB, OpenDaylight, pvilas/raft, Raft4WS, Raft-JVM, r4j, liferaft, benbjohnson/raft.js, dannycoates/raft-core, kanaka/raft.js, skiff, ocaml-raft, py-raft, simpleRaft, floss, giraft, harryw/raft, zodiac-prime, hoverbear/raft, akka-raft, archie/raft, cb372/raft, chelan, ckite, scalaraft, lite-raft, C5, yora, srned/Prez, fxsjy/Ins

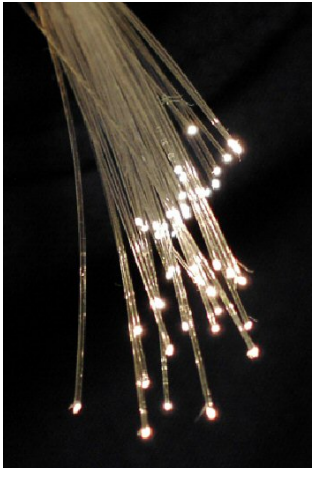
https://pbs.twimg.com/profile_images/592837647577587714/eNMItpUG_400x400.png

Part 7

Network partitioning



Network partitioning



+

http://upload.wikimedia.org/wikipedia/commons/b/b9/Kitchen-Scissors.jpg
http://upload.wikimedia.org/wikipedia/commons/4/49/Fibreoptic.jpg

CAP theorem

- Systems' properties:
  1. **C**onsistency

CAP theorem

- Systems' properties:
  1. **C**onsistency
  2. **A**vailability

CAP theorem

- Systems' properties:
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CAP theorem

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CAP theorem

Having C/A/P – choose (at most) 2 of 3!

CAP theorem

- Systems' properties:
  1. **C**onsistency
  2. **A**vailability
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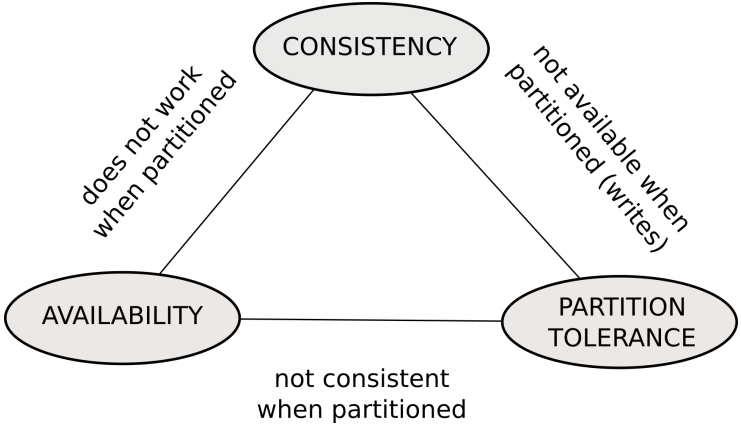

CAP theorem

Having C/A/P – choose (at most) 2 of 3!

Example systems' classification

- Having:
  - **C**onsistency
  - **A**vailability
  - **P**artition-tolerance

Example systems' classification

- Having:
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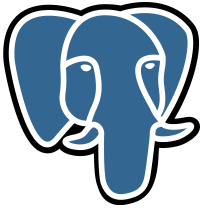
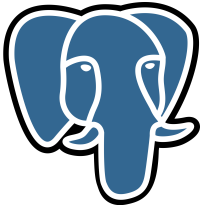
- Examples:
  - PostgreSQL – **CA**P



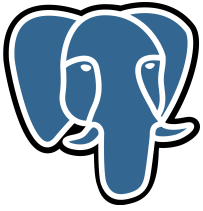
Example systems' classification

- Having:
  - **C**onsistency
  - **A**vailability
  - **P**artition-tolerance
- Examples:
  - PostgreSQL – **CA**P
  - MongoDB – **C**A**P**



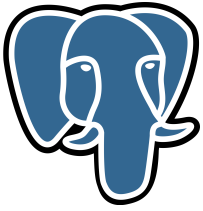
Example systems' classification

- Having:
  - **C**onsistency
  - **A**vailability
  - **P**artition-tolerance
- Examples:
  - PostgreSQL – **CA**P
  - MongoDB – **CP**
  - Cassandra – C**AP**



Example systems' classification

- Having:
  - **C**onsistency
  - **A**vailability
  - **P**artition-tolerance
- Examples:
  - PostgreSQL – **CA**P
  - MongoDB – **C**A**P**
  - Cassandra – C**AP**
- In reality:
  - Modulo bugs! :-)
  - Often configuration-dependent...
  - "*Call me maybe*" series



mongoDB

cassandra

https://upload.wikimedia.org/wikipedia/commons/2/29/Postgresql_elephant.svg
https://upload.wikimedia.org/wikipedia/commons/5/5e/Cassandra_logo.svg
https://upload.wikimedia.org/wikipedia/en/e/eb/MongoDB_Logo.png

Part 8

Synchronizing time

- Given events:
  - **A** (at **nodeA**)
  - **B** (at **nodeB**)
- Did **A** happened before **B**?

Synchronizing time

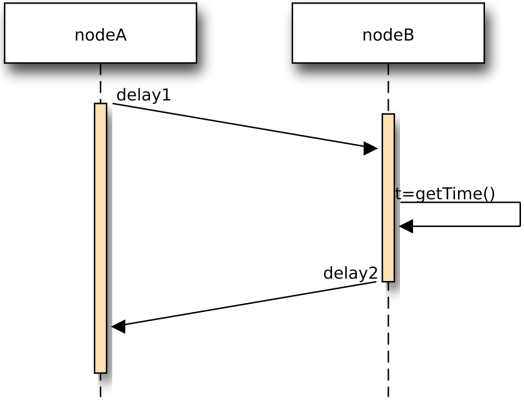
- Given events:
  - **A** (at **nodeA**)
  - **B** (at **nodeB**)
- Did **A** happened before **B**?
- Check their time!

Synchronizing time

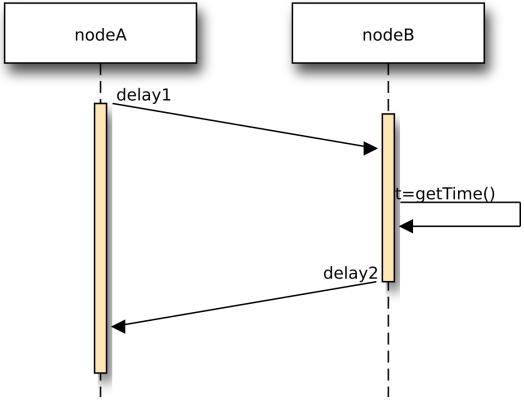
- Given events:
  - **A** (at **nodeA**)
  - **B** (at **nodeB**)
- Did **A** happened before **B**?
- Check their time!
  - Are clocks in sync? (*clock skew*)
    - How precise?
    - What about latencies?
  - Will clocks remain in sync? (*clock drift*)

http://1.bp.blogspot.com/-m4Wd15SQ3eY/T75YMmeYwrI/AAAAAAAAAaw/nrH2BxGSimw/s320/Clock+art-Salvador+Dali.jpg

Cristian's algorithm

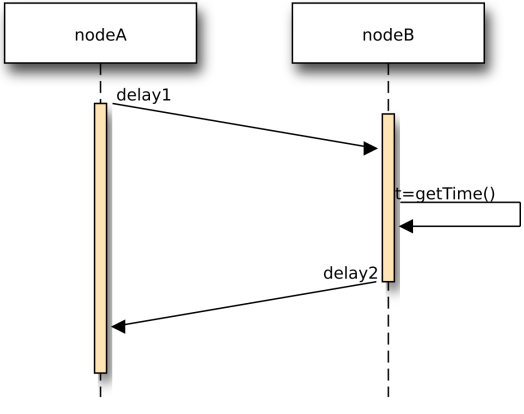


Cristian's algorithm



- Assuming $delay1 = delay2$
- New time: $t_1 = t + \frac{RTT}{2}$
- Where:
  - RTT – Round Trip Time
  - t_1 – new local time
  - t – time from remote party

Cristian's algorithm



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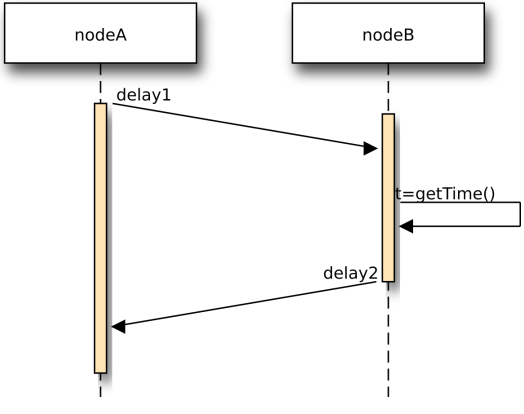
- Fairly Simple™;-)
- Often imprecise

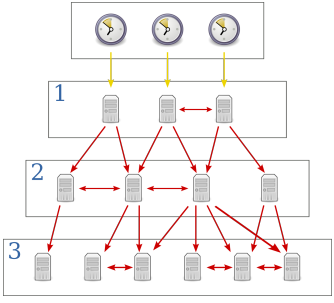
Cristian's algorithm



- Assuming $delay1 = delay2$
- New time: $t_1 = t + \frac{RTT}{2}$
- Where:
  - RTT – Round Trip Time
  - t_1 – new local time
  - t – time from remote party
- Fairly Simple™;-)
- Often imprecise
- Single point of synchronization
- Does not scale

NTP's algorithm

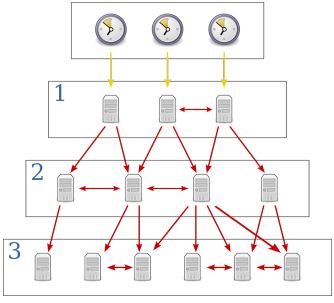
- **N**etwork **T**ime **P**rotocol

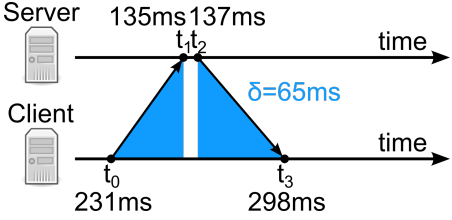


- More clock sources
- Better scalability

NTP's algorithm

- **N**etwork **T**ime **P**rotocol





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NTP's algorithm

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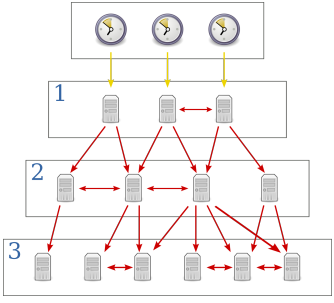

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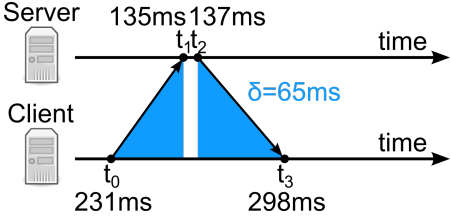
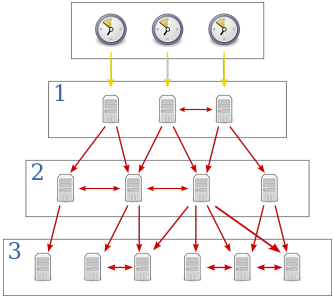


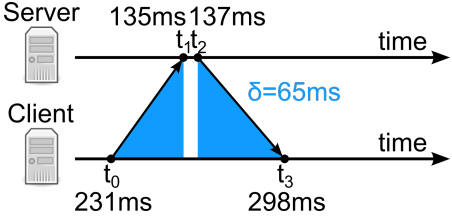
- Better *RTT* estimation
- Probabilistic analysis of data
- Continuous operation

NTP's algorithm

- **N**etwork **T**ime **P**rotocol



- More clock sources
- Better scalability



- Better *RTT* estimation
- Probabilistic analysis of data
- Continuous operation

- Commonly use in the Internet
- Still clocks skew and drift. . .

http://upload.wikimedia.org/wikipedia/commons/c/c9/Network_Time_Protocol_servers_and_clients.svg

http://upload.wikimedia.org/wikipedia/commons/8/8d/NTP-Algorithm.svg

Now what if...

- Cannot solve?

Now what if...

- Cannot solve?
  - Step back
  - Find a different path...

Now what if...

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- What is REALLY needed?

Now what if...

- Cannot solve?
  - Step back
  - Find a different path...
- What is REALLY needed?
  - Ordering knowledge
  - "What happened first?"

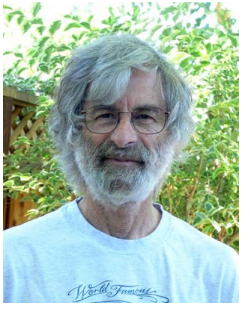
Now what if...

- Cannot solve?
  - Step back
  - Find a different path...
- What is REALLY needed?
  - Ordering knowledge
  - "What happened first?"
- Can be done without time...

Part 9

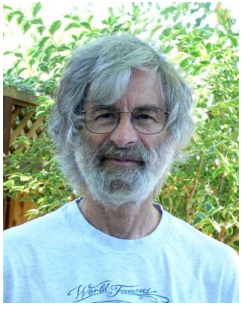
Logical ordering

- **L**amport's **T**ime **S**tamp
- Proposed by *Leslie Lamport*
- Establishes *happens-before* relation



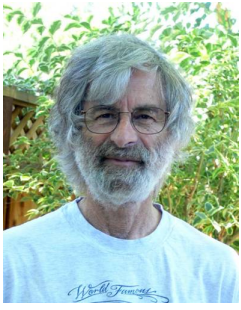
Logical ordering

- **L**amport's **T**ime **S**tamp
- Proposed by *Leslie Lamport*
- Establishes *happens-before* relation
- Each process has counter *lts*
- Initially $lts = 0$



Logical ordering

- **L**amport's **T**ime **S**tamp
- Proposed by *Leslie Lamport*
- Establishes *happens-before* relation
- Each process has counter *lts*
- Initially $lts = 0$
- Algorithm:
  - Before sending: $lts = lts + 1$
  - Include counter in the message
  - When receiving: $lts = max(lts, msg\_lts) + 1$
- Also can increment at will

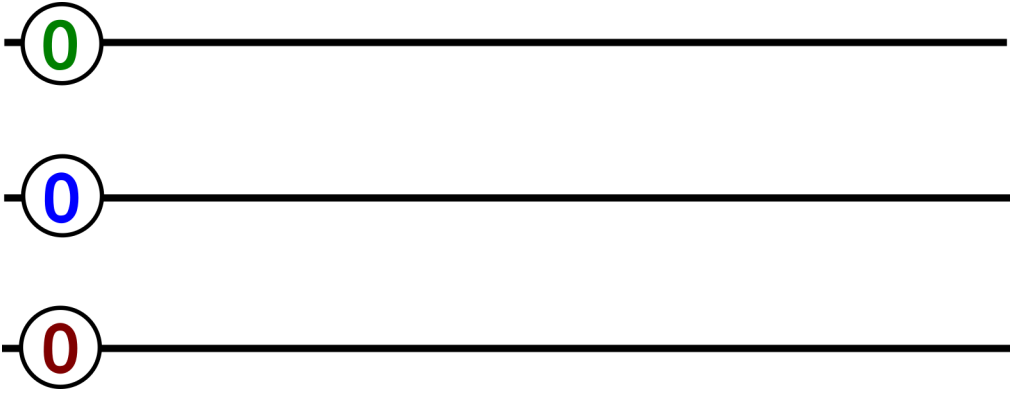


https://upload.wikimedia.org/wikipedia/commons/5/50/Leslie_Lamport.jpg

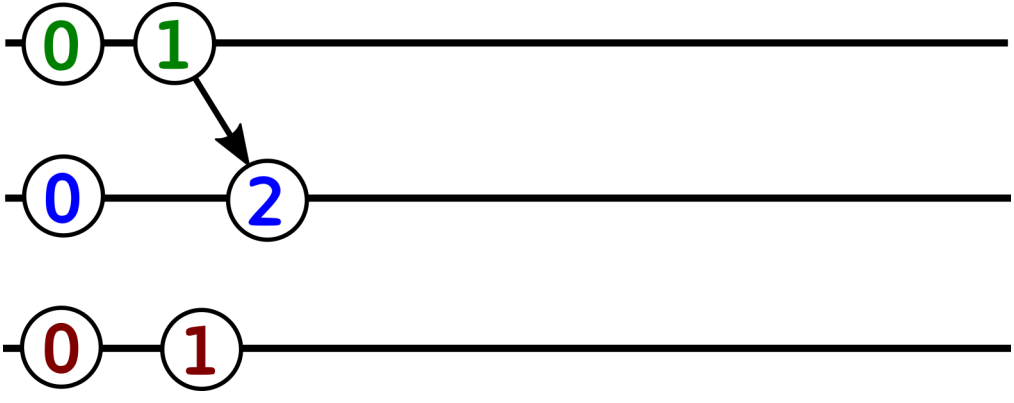
Come again?

http://lshss.pubs.asha.org/data/Journals/LSHSS/930529/LSHSS_45_3_220fig0.jpeg

Example



Example



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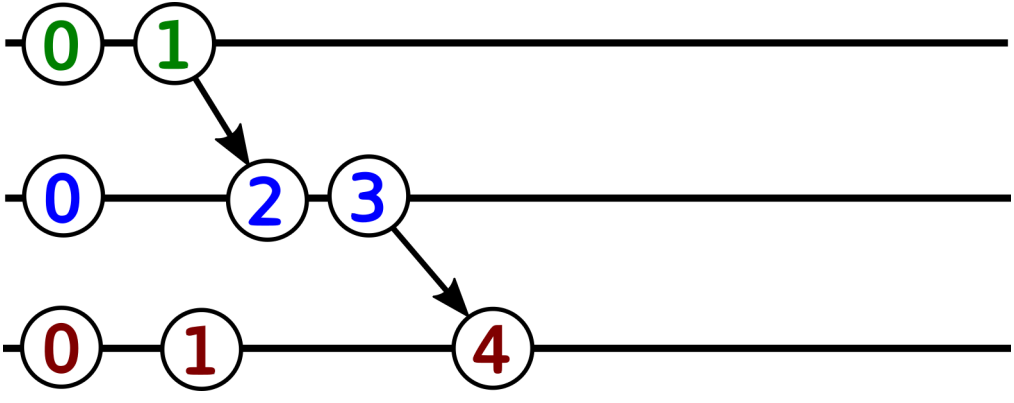
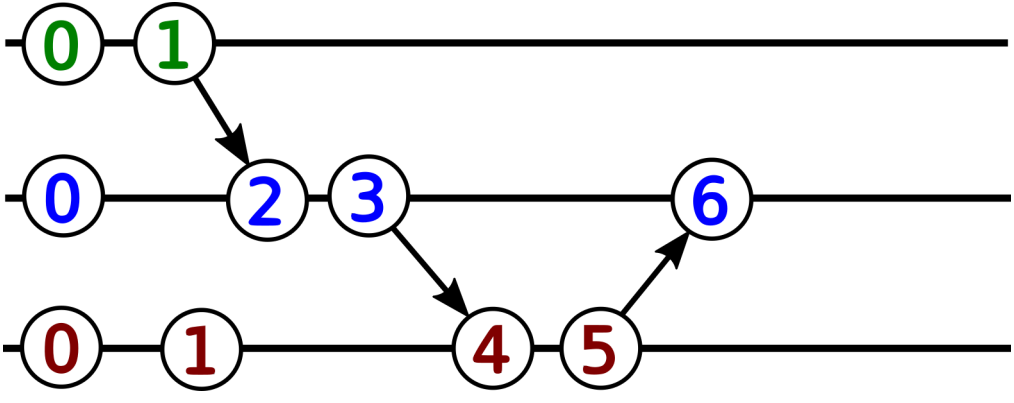
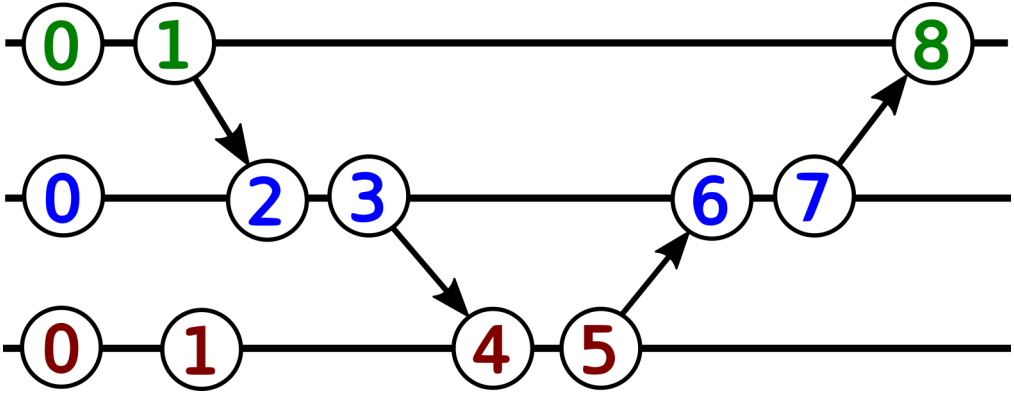


Example



Example



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- Events: A and B
- With timestamps: $C(A)$ and $C(B)$

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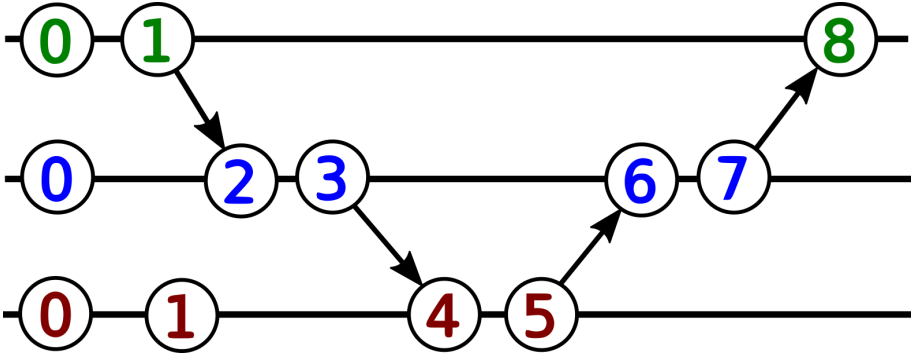
  - But **not** $B \rightarrow A$
- Cause-effect ordering!

Let's check!

$$C(A) < C(B) \Leftrightarrow A \rightarrow B \vee A \parallel B$$



Lamport's timestamps at . . .

- Pretty much everywhere. . . ;)
- Including. . .

Lamport's timestamps at . . .

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Lamport's timestamps at . . .

- Pretty much everywhere. . . ;)
- Including. . .

- Part of BTS software:
  - WCDMA OAM
  - SRAN OAM
  - Cloud OAM
- Distributed service registration
- Introduces logical ordering
- Registration updates' ordering

https://upload.wikimedia.org/wikipedia/commons/0/02/Nokia_wordmark.svg

Part 10

Enhanced logical ordering

- Similar to Lamport's timestamps
- Detects parallel events

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- Each process has vector of counters $vc = [c1, c2, ..., cN]$
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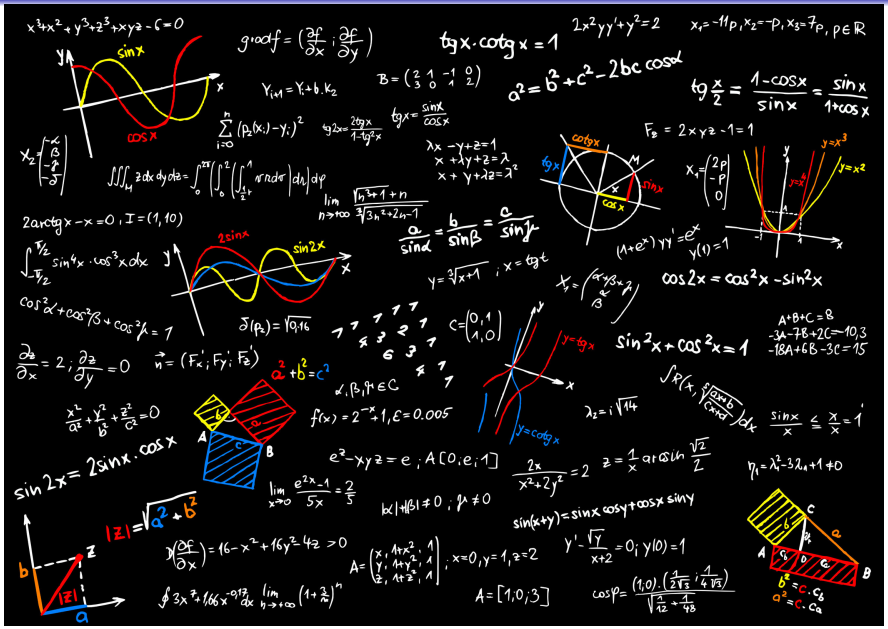
Enhanced logical ordering

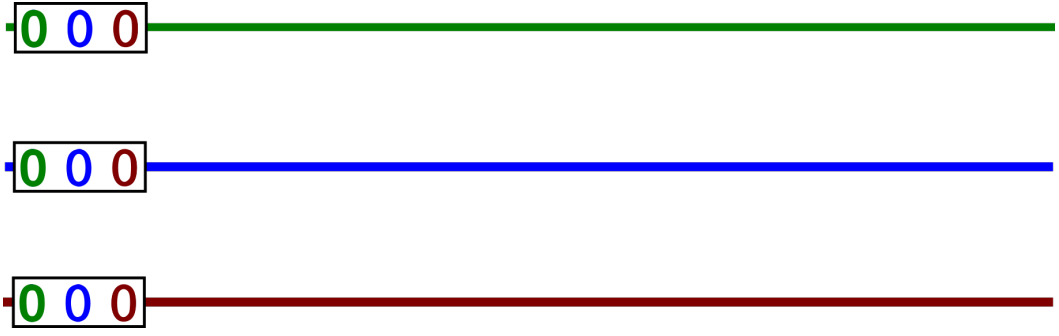
- Similar to Lamport's timestamps
- Detects parallel events
- Each process has vector of counters $vc = [c1, c2, ..., cN]$
- Initially $vc = [0, 0, ..., 0]$
- Algorithm:
  - On i-th node
  - Before sending: $vc[i] = vc[i] + 1$
  - Include vector in the message
  - When receiving:
    - $\forall j \neq i : vc[j] = max(vc[j], msg\_vc[j])$
    - $vc[i] = vc[i] + 1$
- Also can increment local counter at will

You don’t say...

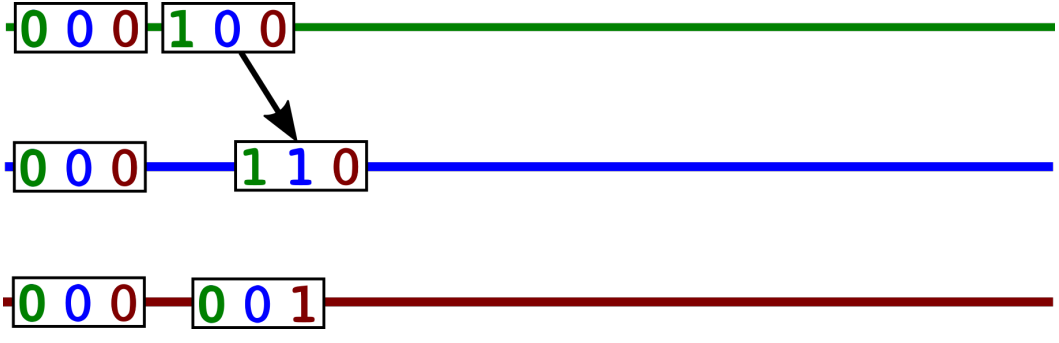


http://syosseths.com/z/acapics/mathslide.jpg

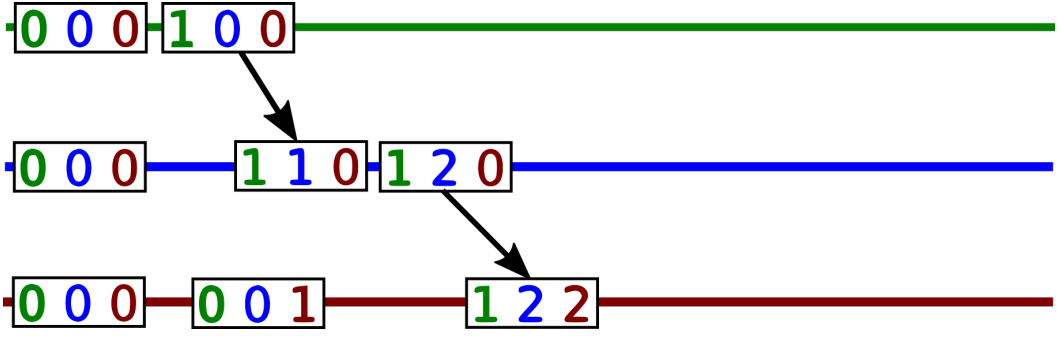
Example



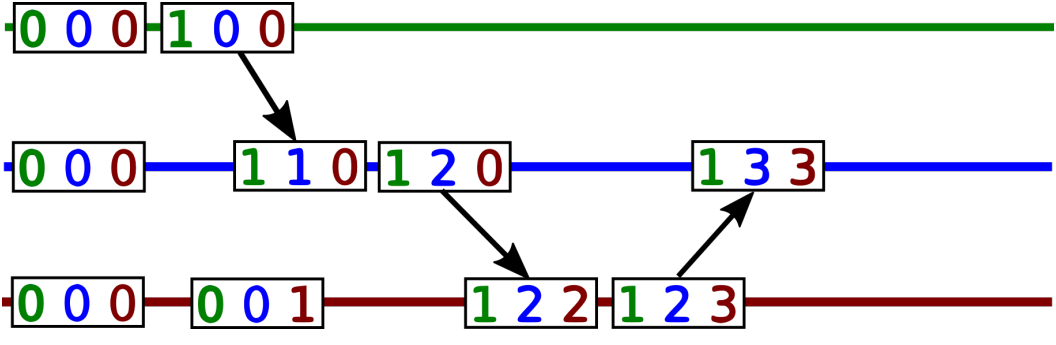
Example



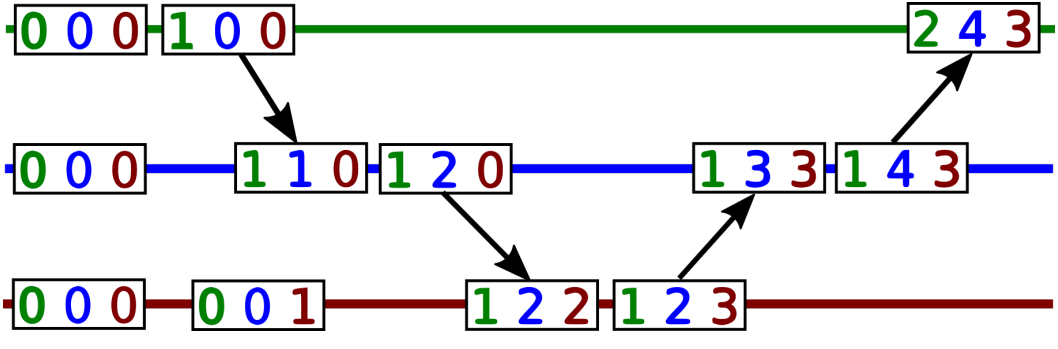
Example



Example



Example



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  - $vc_1 \leq vc_2 \Leftrightarrow \forall i : vc_1[i] \leq vc_2[i]$
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  - $vc_1 < vc_2 \Leftrightarrow vc_1 \leq vc_2 \wedge \exists i : vc_1[i] < vc_2[i]$
- Causality:
  - $A \rightarrow B \Leftrightarrow vc(A) < vc(B)$
  - $A \parallel B \Leftrightarrow \neg(vc(A) \leq vc(B)) \wedge \neg(vc(B) \leq vc(A))$

Let's check!

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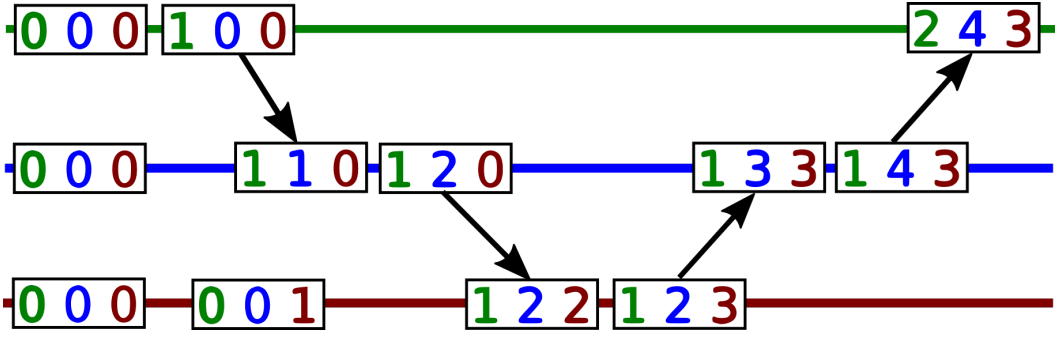
- $A \parallel B \Leftrightarrow \neg(vc(A) \leq vc(B)) \wedge \neg(vc(B) \leq vc(A))$



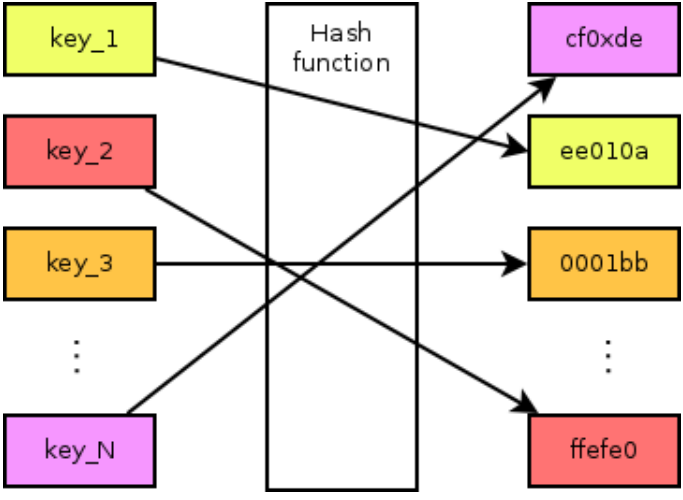
Vector clocks inside Riak

- Riak:
  - NoSQL database
  - Based on "Dynamo" paper
- VC for eventual consistency
- Help solve conflicts:
  - Resolve duplicates
  - Detect latest version
  - Detect simultaneous updates

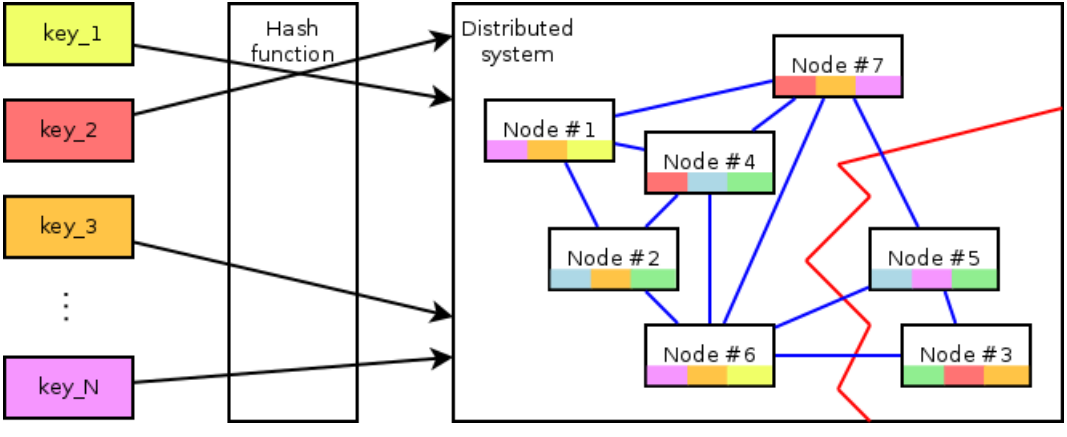
https://upload.wikimedia.org/wikipedia/en/8/8e/Riak_distributed_NoSQL_key-value_data_store_logo.png

Part 11

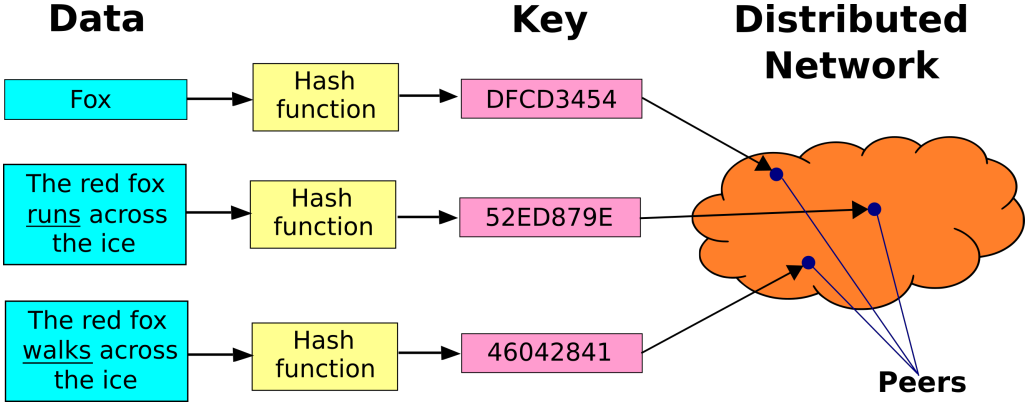
Hash table


key_1
key_2
key_3
key_N
Hash function
cf0xde
ee010a
0001bb
ffefe0

Distributed Hash Table (DHT)



Keys distribution



https://upload.wikimedia.org/wikipedia/commons/9/98/DHT_en.svg

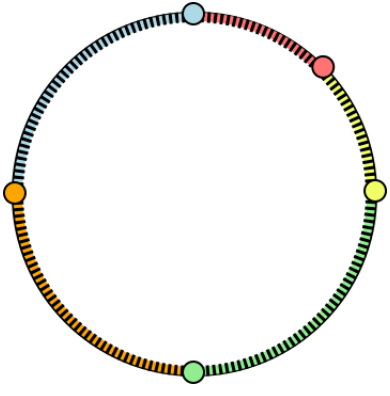
DHTs everywhere

- Common since the end of ’90
- Base of most NoSQL DBs
- Advantages:
  - Massive storage
  - Decentralized
  - Fault tolerant
  - Scalable

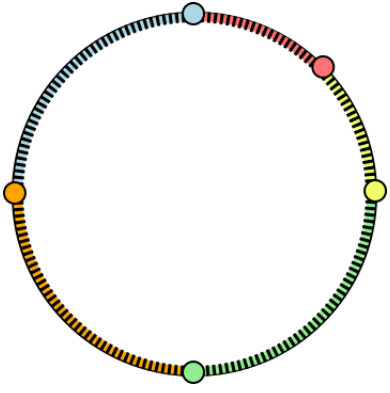
https://upload.wikimedia.org/wikipedia/commons/5/5e/Cassandra_logo.svg
http://www.gluster.org/images/antmascot.png?1432254431
https://upload.wikimedia.org/wikipedia/en/8/8e/Riak_distributed_NoSQL_key-value_data_store_logo.png
https://upload.wikimedia.org/wikipedia/commons/6/6d/Transmission_icon.png
https://upload.wikimedia.org/wikipedia/en/9/9f/UTorrent_%28logo%29.png
https://upload.wikimedia.org/wikipedia/commons/9/9e/Qbittorrent_logo.png
https://upload.wikimedia.org/wikipedia/commons/f/ff/Qbittorrent_mascot.png
https://upload.wikimedia.org/wikipedia/en/d/d5/BitComet_logo.svg
https://upload.wikimedia.org/wikipedia/commons/0/0a/Shareaza.png
https://upload.wikimedia.org/wikipedia/en/d/d6/Logo_of_BearShare_from_Website.jpg

Part 12

The ring

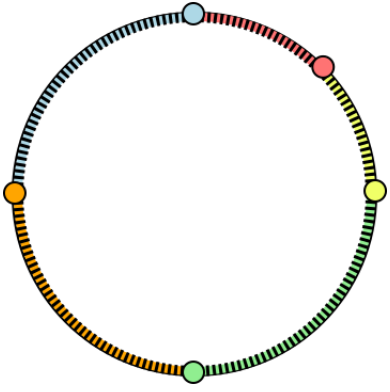


The ring



- Ring-organized
- m-bits (2^m possible entries)
- Ordered clock-wise
- Node keeps preceding keys

The ring



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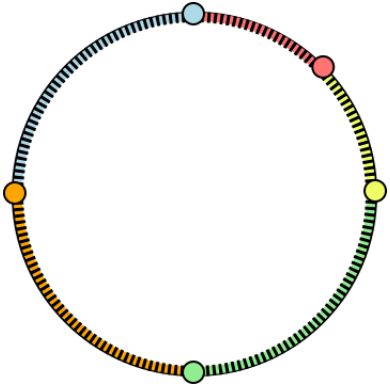

- Ring-organized
- m-bits (2^m possible entries)
- Ordered clock-wise
- Node keeps preceding keys
- Nodes hashed by:
  - Address (IP?)
  - Port
- Keys:
  - User's hash
  - Share key space with nodes
- *SHA-1* commonly used

Finger table

- Each node keeps own
- m-entries
- $(n + 2^i)\%2^m$
- Where:
  - i – entry number
  - n – node's number
  - m – hash bits

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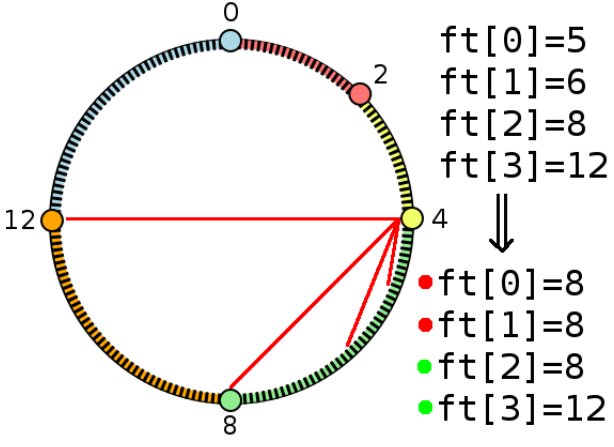
- Here: $n = 4$, $m = 4$
- i.e. $2^4 = 16$ entries



One ring to hash them all!

https://upload.wikimedia.org/wikipedia/commons/b/b7/Unico_Anello.png

Query algorithm

1. Having query for k
2. If has k – return it

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3. $next = \max(ft[i] : i \in \langle 0; m) \wedge ft[i] \leqslant k)$
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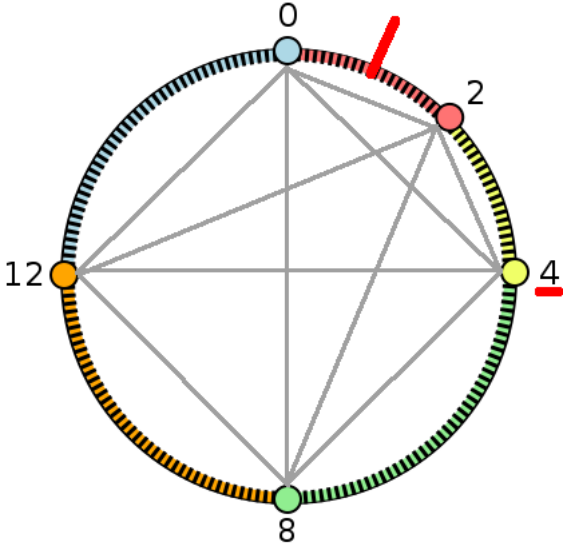
5. If has $next$ – return it
6. Else return first successor

Query example



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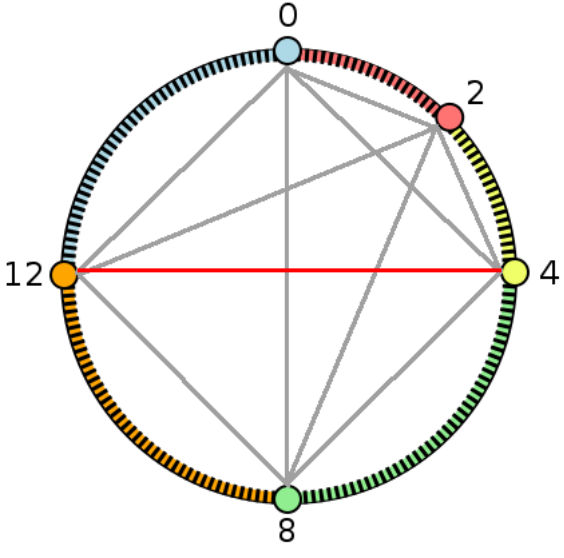
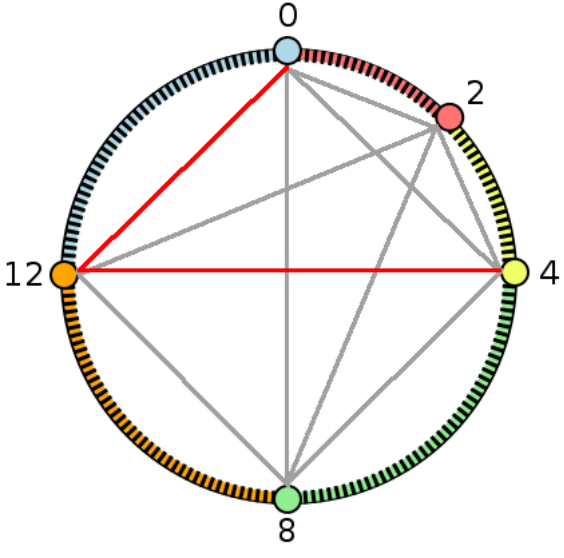
Query example



- Node 4 – query 1
- Finger tables:
  1. $n = 4$
     - $ft[0] = 8$
     - $ft[1] = 8$
     - $ft[2] = 8$
     - $ft[3] = 12$

Query example



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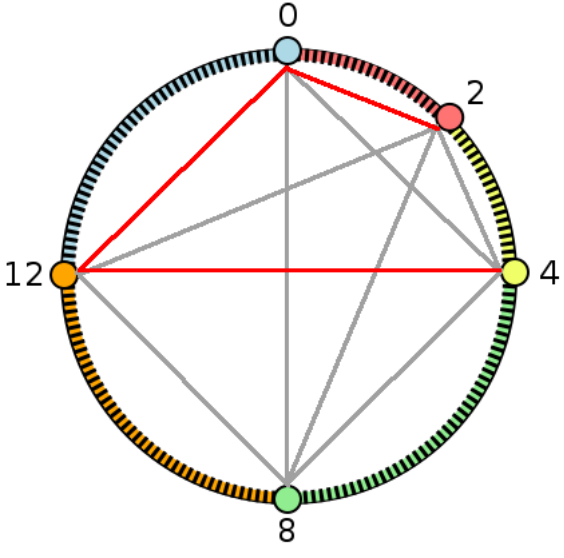
     - $ft[3] = 12$
  2. $n = 12$
     - $ft[0] = 0$
     - $ft[1] = 0$
     - $ft[2] = 0$
     - $ft[3] = 4$

Query example



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     - $ft[2] = 0$
     - $ft[3] = 4$
  3. $n = 0$
     - $ft[0] = 2$
     - $ft[1] = 2$
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Additional notes

- $O(\log N)$ memory
- (Amortized) $O(\log N)$ lookup
- Considered almost $O(1)$

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  - Nodes leaving – merging ranges
  - Nodes crashing = nodes leaving

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  - Nodes leaving – merging ranges
  - Nodes crashing = nodes leaving
- Failures handing:
  - Duplication of data
  - More entries per finger table
  - Keeping few predecessors
  - Monitoring neighborhood

Part 13

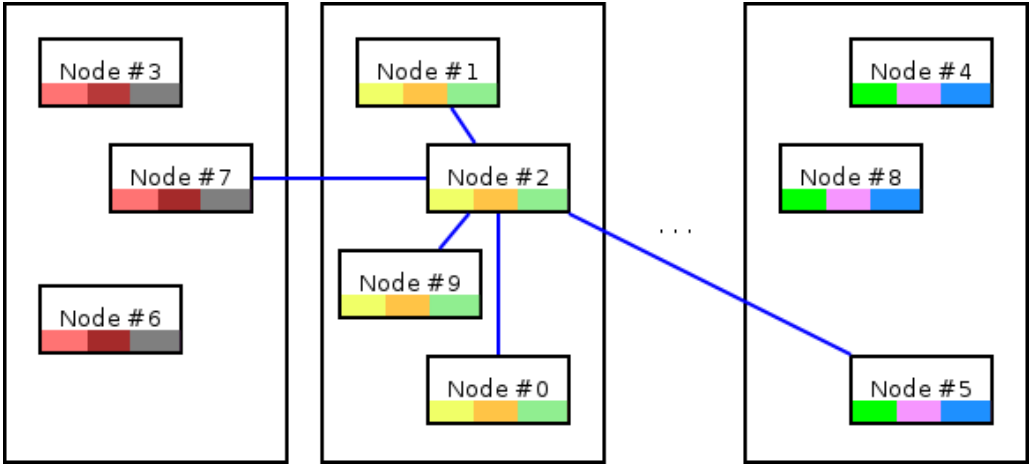
Idea

- Split space:
  - *k affinity groups*
  - $k \approx \sqrt{N}$

Idea

- Split space:
  - *k affinity groups*
  - $k \approx \sqrt{N}$
- Group based on node's hash
- Node in a group knows:
  - All members of its group
  - One node per other groups
  - All group's hashes

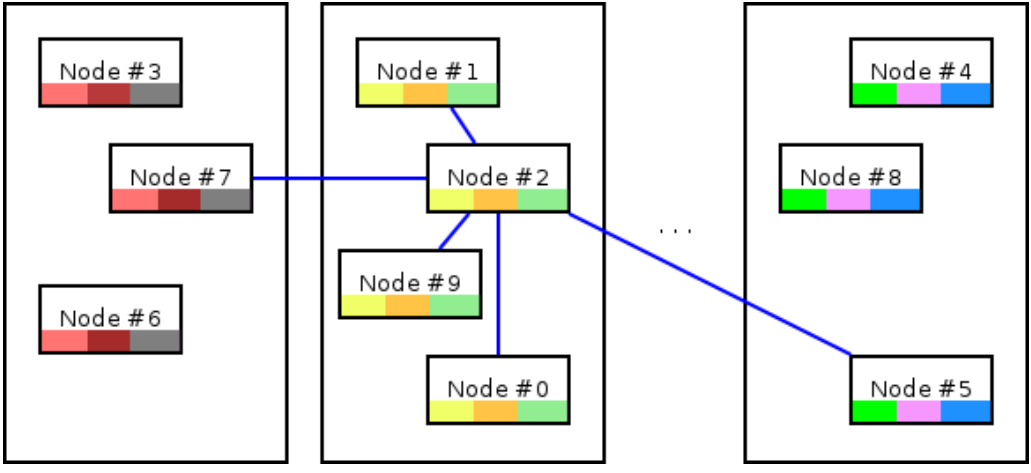
Example - node 2



Local query

Querying for key from the same affinity group

Node #2 querying "yellow" key



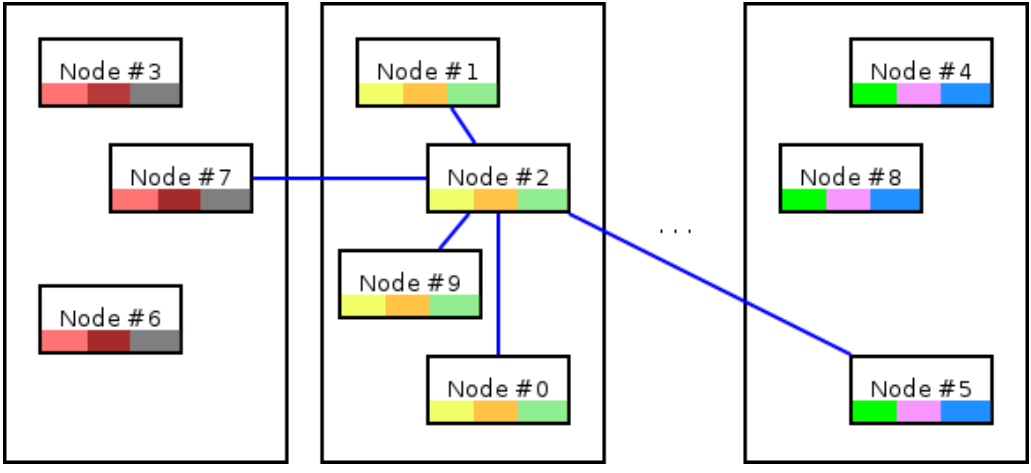
It’s here!

http://asalesguyrecruiting.com/wp-content/uploads/2014/03/Oh-Hell-Yeah-566x372.png

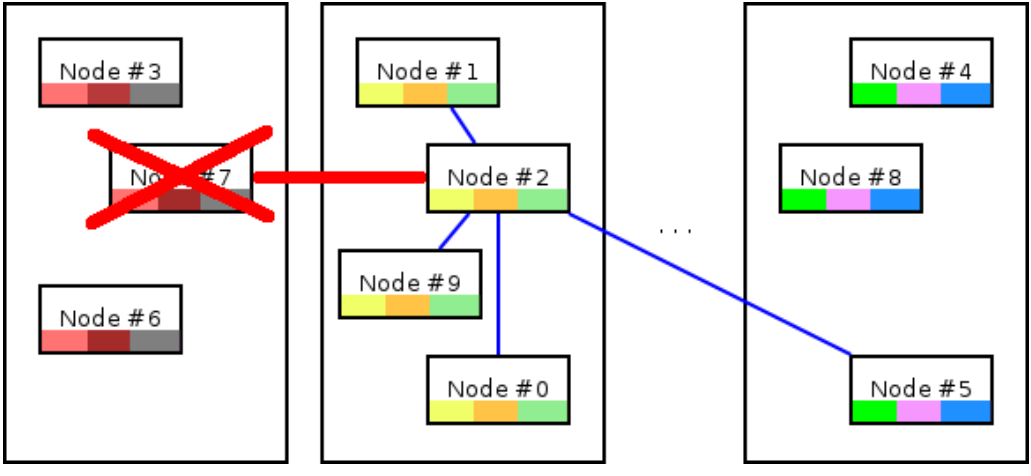
Remote query

Querying for key from different affinity group

Node #2 querying "red" key



Node #2 querying "red" key



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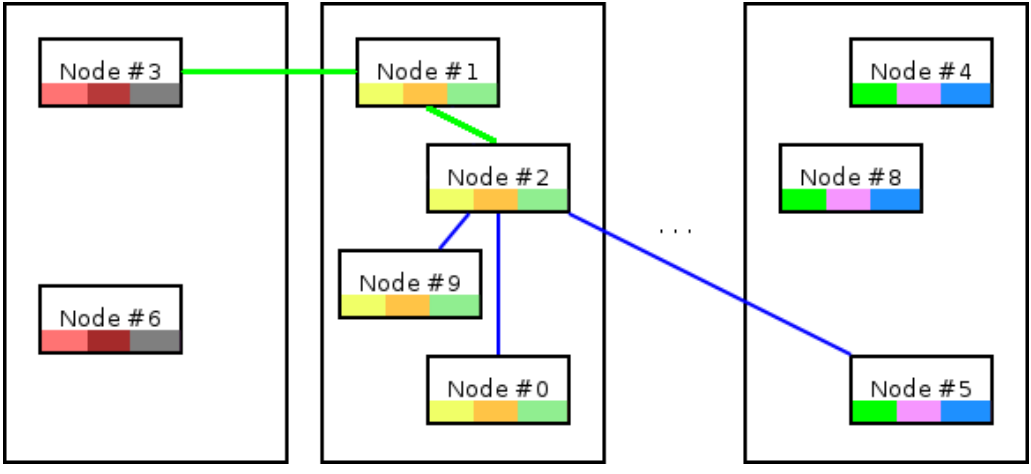
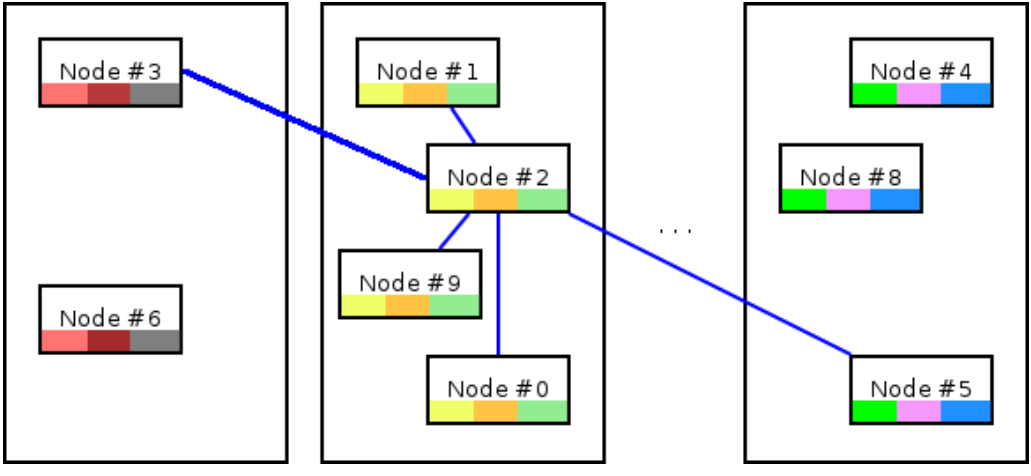


Node #2 querying "red" key



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  - Nodes leaving – less replication
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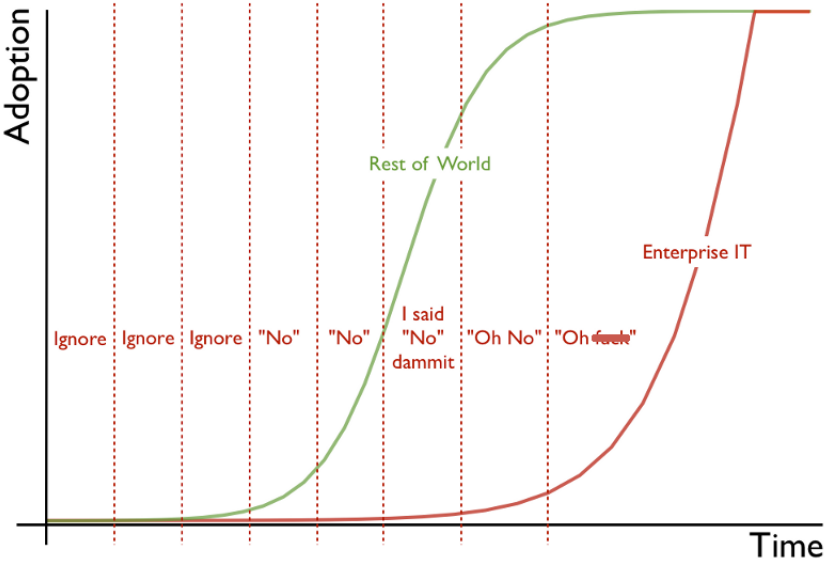
- Other scenarios:
  - Initialization – query own affinity group
  - Nodes joining – more data replicated
  - Nodes leaving – less replication
  - Nodes crashing = nodes leaving
- Failures handing:
  - Monitoring own affinity group
  - Querying others for affinity neighbors

Part 14

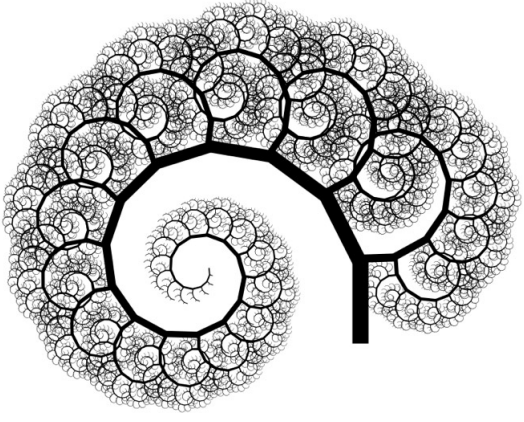
Cloud @ enterprises



http://enterpriseitadoption.com/images/adoption_cycle.png

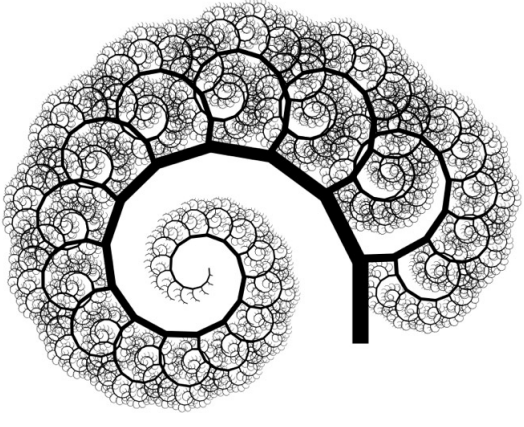
More to learn...

- Coursera:
  - Cloud computing concepts – part 1 & 2
  - Cloud computing applications
  - Cloud networking



More to learn...

- Coursera:
  - Cloud computing concepts – part 1 & 2
  - Cloud computing applications
  - Cloud networking
- Other problems/algorithms:
  - Mutual exclusion
  - Snapshoting
  - Multicast problem
  - Transactions



More to learn...

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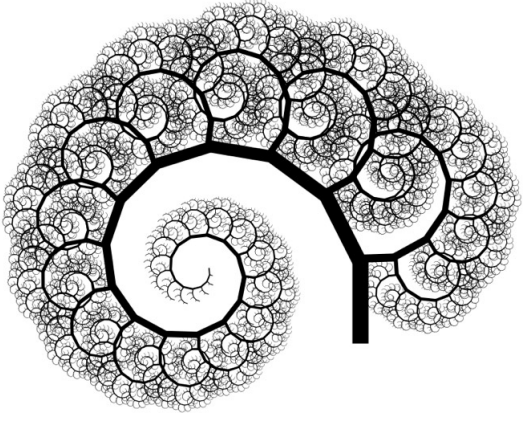

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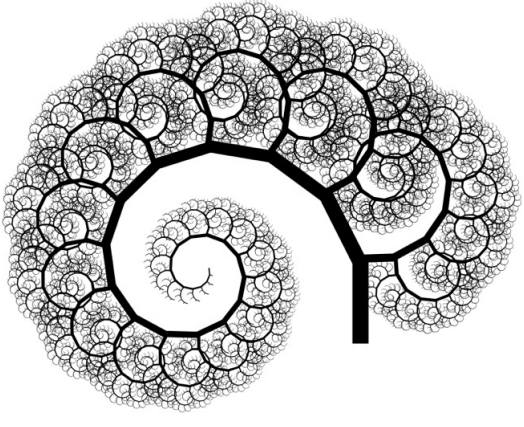
  - NewSQL
- . . .



http://matthewjamestaylor.com/img/recursive-drawing/pubic-hair.jpg

Keep learning

Johann Wolfgang von Goethe

What we do not understand we do not possess.

Keep learning

Johann Wolfgang von Goethe

What we do not understand we do not possess.

- Knowledge is power
- Better understanding
- Control over environment

Questions?