CS 455: Introduction To Distributed Systems [Architectures/Topology]

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Frequently asked questions from the previous class survey

- None
  - That's a first for the semster

Topics covered in this lecture

- Decentralized architectures
- Topologies
  - Regular graphs
  - Random graphs
  - Small world graphs
  - Power law networks

Ryan Stern and Shrideep Pallickara. On the Role of Topology in Autonomously Coping with Failures in Content Dissemination Systems. Proceedings of the *ACM Cloud and Autonomic Computing Conference*. Miami, USA. 2013.

Decentralized Architectures

Decentralized architectures

- Server may be split up into logically equivalent parts
  - Each part operates on its share of the dataset
  - Balance the load
- Interaction between processes is **symmetric**
  - Each **peer** acts as a client and a server

Structured Peer to Peer Architectures: Distributed hash tables

- **Data items** are assigned an identifier from a large random space
  - 128-bit UUIDs or 160-bit SHA-1 digests
- **Nodes** are also assigned a number from the ***same*** identifier space

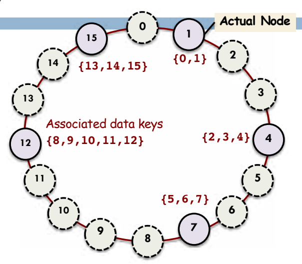
Crux of the DHT problem

- Implement an efficient, **deterministic** scheme to *map data item to node*
- When you look up a data item?
  - Network address of node holding the data is returned

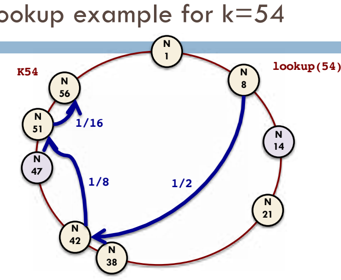
A quick look at the Chord system

- Nodes are organized into a **ring**
- Data item with key **k** is mapped to a node with the smallest **id ≥ k**
  - Also referred to as `successor(k)`

Mapping of data items to nodes in Chord



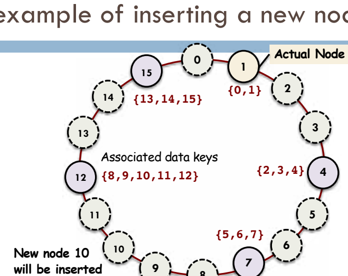
Chord lookup example for k=54



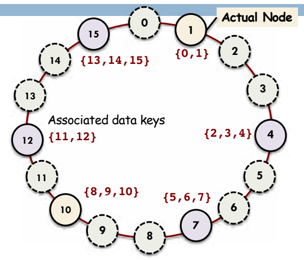
When a node wants to join?

- Generate a random id
  - Probability of collisions is low
- **`lookup(id)`**
  - Will return `successor(id)`
- Contact `successor(id)` and its predecessor
  - Insert self in the ring
  - **Transfer** data items

An example of inserting a new node



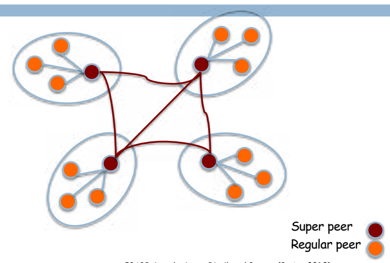
An example of inserting a new node



Unstructured P2P networks that rely on random graphs

- Maintain connections to randomly chosen live nodes
- To locate a data item
  - **Flood** the network

Hierarchical organization of nodes



Superpeer networks

- The client-superpeer relationship is **fixed**
  - When a peer joins, it *attaches* itself to the superpeer and stays attached till it leaves
- Superpeers are expected to be *long-lived* processes with *high-availability*
- Selecting nodes that are eligible to be superpeers?
  - Closely related to the leader **election** problem

Small Worlds

Stanley Milgram's experiment on social networks

- In 1967 he mailed 160 letters
- People were randomly chosen from Omaha, Nebraska
- Objective was to pass their letter
  - Target: Stock broker in Boston, MA
  - Constraint: Use *intermediary* known to them on a **first-name** basis

Results: It's a small, small world

- 42 letters made it through
  - Median was just 5.5. intermediaries
  - US Population in 1967: 200 million
- First demonstration of what is known as the **small world** effect

Intuitively it seems that the pathlengths should have been much higher

- People's social circle is cliquish or **clustered**
- People you know, know each other

The key is the distribution of links within social networks

- Some acquaintances are relatively isolated
- Some have wide ranging connections
  - Play a critical role in bringing network **closer** together
- Milgram experiment
  - ¼ of the successful chains passed through a local storekeeper

The Hollywood Network:

- Here we organize all actors in a graph
- If they have co-starred with someone in a movie
  - They have a direct link to them (1 hop)
- Some actors have more links than others because they have acted in so many movies
  - E.g. Kevin Bacon

The Hollywood Network: 6 degrees of Kevin Bacon

- John Carradine: 4000 links
- Robert Mitchum: 2905 links
- But acting in the most movies does not always translate into shortest hops to a random node in the network
- Rankings:
  - Rod Steiger: 2.53
  - Donald Pleasence: 2.54
  - Martin Sheen, Christopher Lee, Robert Mitchum, Charlton Heston
  - Kevin Bacon? 2.79 pathlength and ranked 876^{th}

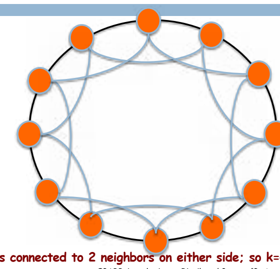
Turns out even a small number of bridges can dramatically reduce pathlengths

Duncan Watts and Steven Strogatz (1998), "*Collective Dynamics of 'Small-World' Networks*," Nature 393, p 440.

Regular Graphs

- Ring of **n** vertices
- Each of the nodes are connected to its **nearest k** neighbors

Example regular graph with k = 4



Each node is connected to 2 neighbors on either side; so k=4

Pathlength in a graph

- Average number of **hops** to reach any node in the system
  - For **each pair** of vertices, compute shortest path
  - Take the average over all pairs
- Gives a sense of **how far apart** points are in the network

Clustering coefficients are a measure of the level of clustering

- For **k** neighbors of a vertex, the number of possible connections between them is

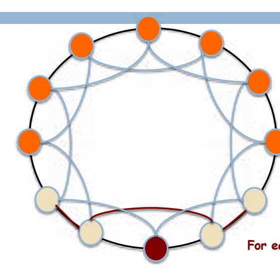
$$C_2^k = \frac{k(k-1)}{2}$$

- **Clustering coefficient** of a vertex
  - Proportion (0 ~ 1) of possible links actually present in graph

Pathlength in Regular graphs

- Approximately **n/2k**
- If **n**=4096 and **k**=8
- Pathlength = **n/2k** = 256
  - Very large!

Clustering Coefficient: Regular graph k=4

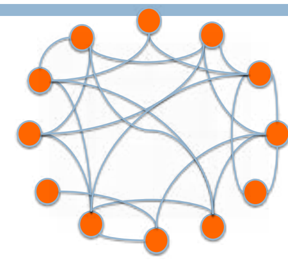


For each vertex = 3/6

Random Graphs

- Opposite of regular graphs
- Vertices are connected to each other at **random**

Random Graphs



Pathlength and clustering coefficients in Random Graphs

- Pathlength is approximately **`log n/log k`**
- Clustering coefficient is approximately: **`k/n`**

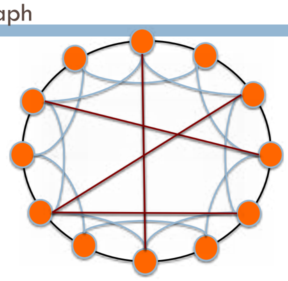
- So, with **`n`**=4096 and **`k`** = 8
  - Average pathlength = `log 4096/log 8` = 4
  - Much better than regular graphs
- Clustering coefficient = 8/4096 = 0.002
  - Much lower than regular graphs

Comparing regular and random graphs

- Regular graph
  - **High clustering**
  - High pathlength

- Random graph
  - Low clustering
  - **Low pathlength**

Small world graphs: Add a few random links to the regular graph



Small world graphs

- High local clustering
- Short global pathlengths

- Implications:
  - Small amount of rewiring needed to promote the transition
  - Transition is barely noticeable at the local level

SCALE FREE NETWORKS

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Power law is a special relationship between two quantities

- The number or frequency of the object
  - Varies as a **power**
- Of some attribute (size) of the object

- Earthquakes
  - The frequency of earthquakes varies as a power of the size of the earthquake

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Power law and Random Networks: Real World examples

- Random networks
  - Eisenhower National Highway System
  - Nodes=Cities, Links=Highways connecting them
  - Most cities served by roughly the same number of highways

- Scale-free networks
  - Airport system
  - Large number of small airports served by a few major **hubs**

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Distribution of links in random networks

- Follows a **bell curve**
- Most nodes have the same number of links

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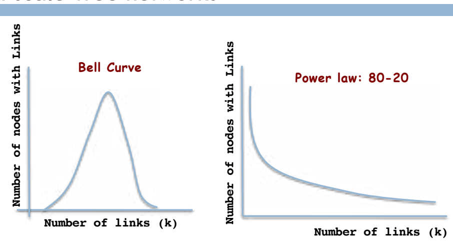
Comparison of the distribution of links in random and scale-free networks



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Growth of scale-free networks

- Addition of nodes
- **Preferential attachment**
  - Nodes prefer to attach to well-connected nodes

- **Result:** Highly connected nodes emerge

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Power law distributions have no peak

- Continuously decreasing curve
- Many small events coexist with a few very large ones
- Imaginary planet:
  - Most people will be really short
  - Among 6 billion people, 1 person would be 8000 ft

Bell Curves vs Power Laws

- Bell Curves
  - Occur very often in nature
  - Exponentially decaying tail
    - Responsible for **absence** of hubs
- Power Laws
  - Emerge during phase transitions
    - Move from chaos to order: Self organization
  - Decay far more slowly
    - Allows for hubs

Why power law networks are called scale-free [1/2]

- In a random network vast majority of nodes have same number of links
  - Nodes deviating from average are rare
  - There is a characteristic **scale** in its connectivity
    - Embodied by the average node
    - Fixed by the peak of the degree distribution

Why power law networks are called scale-free [2/2]

- In a power law network
  - Absence of peak
- No such thing as a characteristic node
  - Continuous hierarchy of nodes spanning from rare hubs to numerous tiny nodes
- No intrinsic scale in power law networks
  - **Scale-free** networks

Achilles' heel in the power law network

- Power law networks are robust to random failures
- Vulnerable to a targeted attack on hubs
- Removal of hubs
  - Disintegrates these networks
  - Breaks them up into tiny non-communicating islands

Coexistence of robustness and vulnerability plays a role in complex systems

- Sea otters in California went nearly extinct because of excessive hunting for its pelts
- In 1911 federal regulators banned hunting them
  - Otters made a dramatic comeback

The case of the otter recovery [1/2]

- Because otters feed on *urchins*, increase in their numbers leads to a decrease in the number of urchins
- With fewer urchins around, the number of *kelps* went up dramatically
- Increased the supply of food for fish
  - Protected the coast from erosion

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The case of the otter recovery [2/2]

- Protection of one species (a hub) altered economy and ecology of the coast line
- Finfish now dominate coastal fisheries
  - Once dedicated to shell fish

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The contents of this slide set are based on the following references

- *Peer-to-Peer: Harnessing the Power of Disruptive Technologies. Edited by Andy Oram. O'Reilly Publishing. ISBN: 0-596-00110-X.*
  [Chapter 14 – Performance by Theodore Hong]
- *Linked: How Everything is Connected to Everything Else and What it Means for Business, Science, and Everyday Life.* Albert-László Barabási. Plume. ISBN: 0452284392/978-0452284395.
  [Chapters 4,5,6, and 7]

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