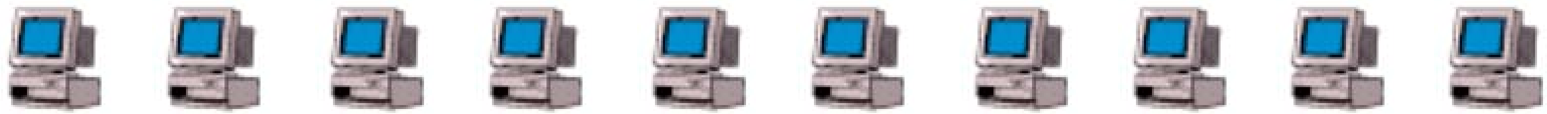
Churn and Selfishness: Two Peer-to-Peer Computing Challenges



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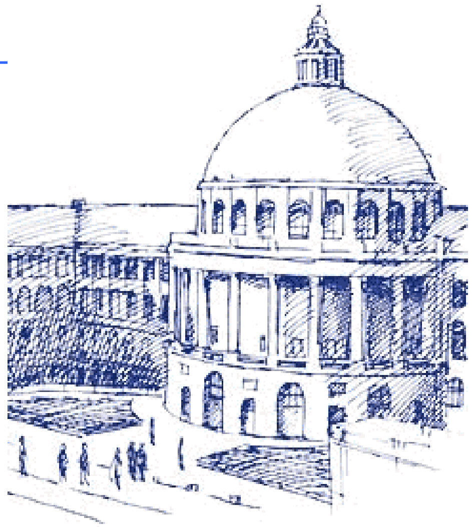
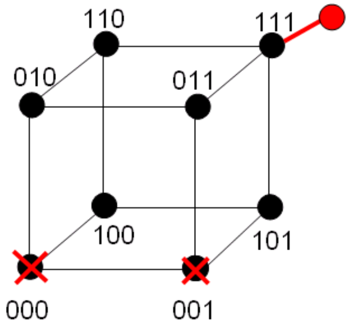
Invited Talk
University of California, Berkeley
380 Soda Hall
March, 2006

Outline of this Talk



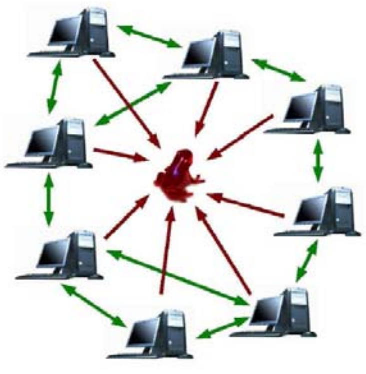
- Current research of our group at ETH
  - Based on our papers at IPTPS 2005 and IPTPS 2006

- Two challenges related to P2P topologies



CHALLENGE 1: Churn

- dynamics of P2P systems,
- i.e., joins and leaves of peers ("churn")
- our approach to maintain desirable properties in spite of churn



CHALLENGE 2: Selfishness

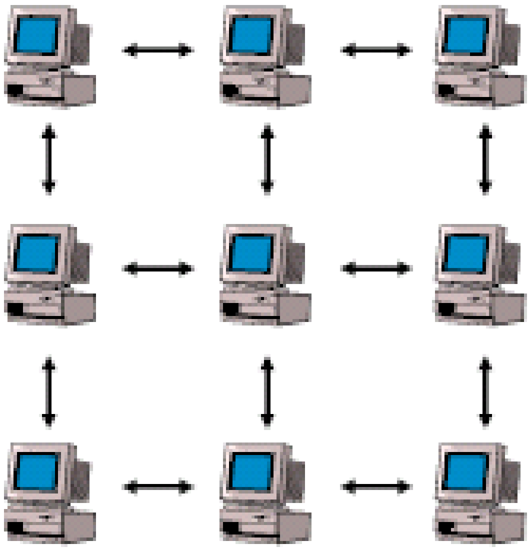
- impact of selfish behavior on P2P topologies
- How bad are topologies formed by selfish peers?
- Stability of topologies formed by selfish peers?

CHALLENGE 1:

Fast and Concurrent Joins and Leaves ("Churn")

Dynamic Peer-to-Peer Systems

- Properties compared to centralized client/server approach
  - Availability
  - Efficiency
  - Etc.
- However, P2P systems are
  - composed of unreliable desktop machines
  - under control of individual users



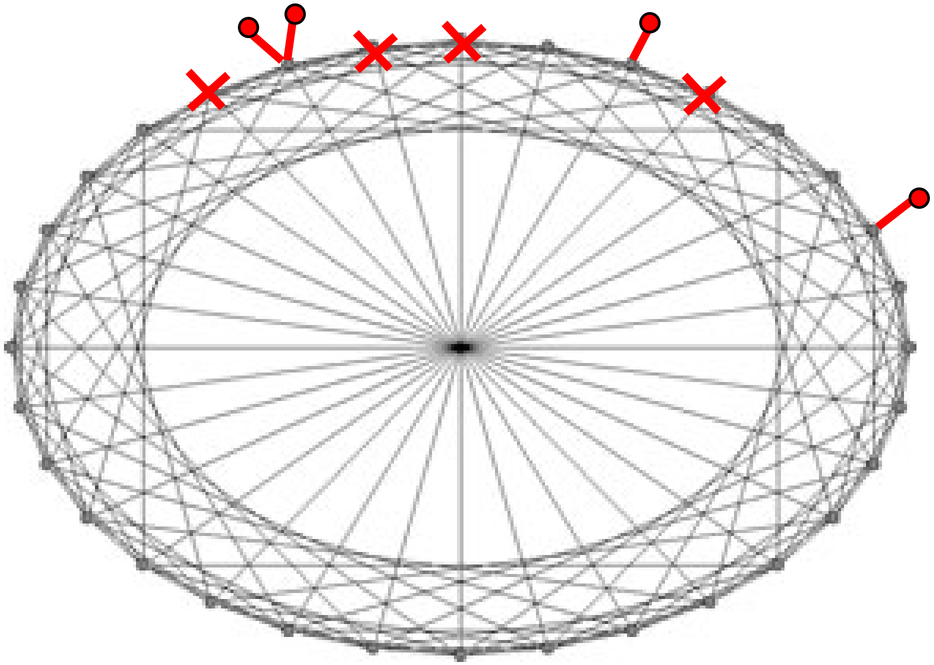
=> Peers may join and leave the network at any time!

Churn

Churn: Permanent joins and leaves

How to maintain desirable properties such as

- Connectivity,
- Network diameter,
- Peer degree?



Challenge 1: Churn

- Motivation for adversarial (worst-case) churn
- Components of our system
- Assembling the components
- Results and Conclusion

Motivation

- Why permanent churn?

  Saroiu et al.: „A Measurement Study of P2P File Sharing Systems“
  Peers join system for one hour on average

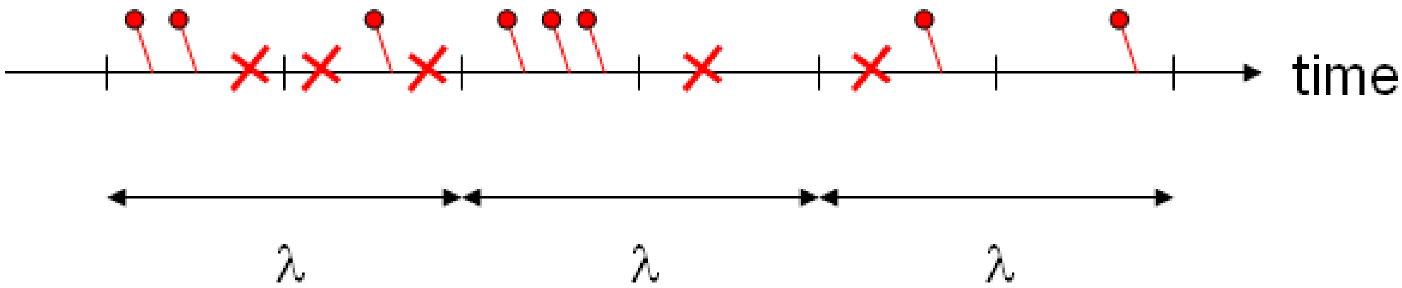
Hundreds of changes per second with millions of peers in the system!

- Why adversarial (worst-case) churn?

  E.g., a crawler takes down neighboring machines (attacks weakest part) rather than randomly chosen peers!

The Adversary

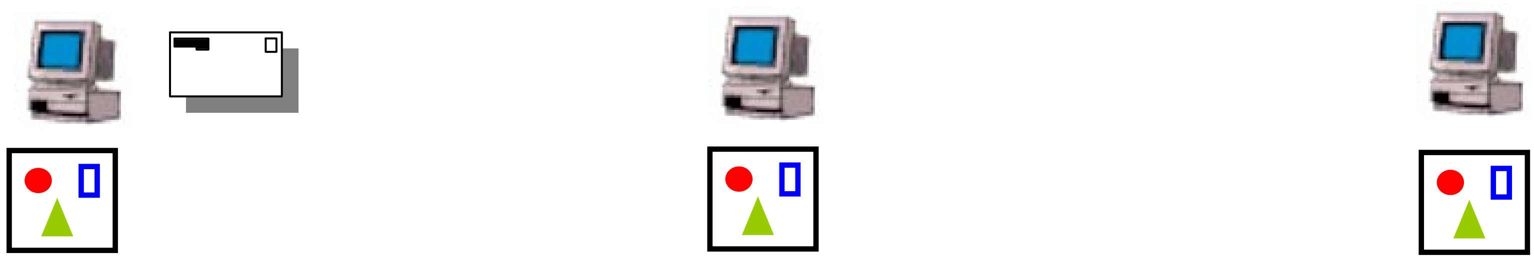
- Model worst-case faults with an adversary *ADV(J,L,λ)*
- *ADV(J,L,λ)* has complete visibility of the entire state of the system
- May add at most *J* and remove at most *L* peers in any time period of length λ



- Note: Adversary is *not* Byzantine!

Synchronous Model

- Our system is synchronous, i.e., our algorithms run in rounds
  - One round: receive messages, local computation, send messages

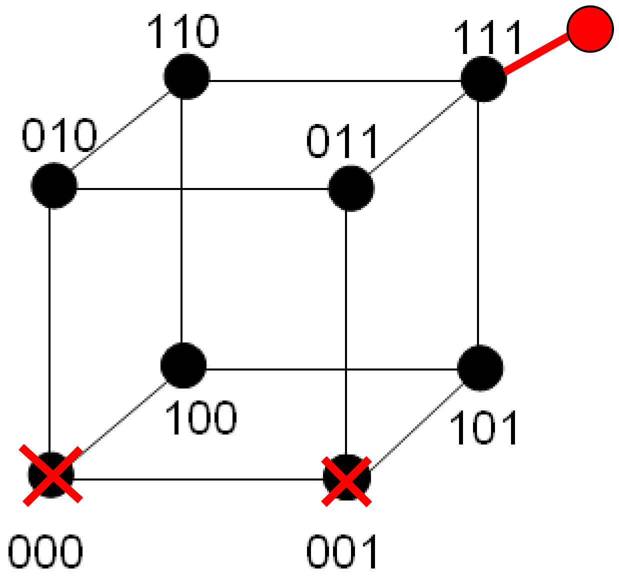


- However: Real distributed systems are asynchronous!
  - Algorithms can still be used: local synchronizers

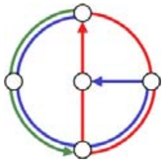
- Notion of time necessary to bound the adversary
  - E.g. 1 round = max. RTT

A First Approach

- Fault-tolerant hypercube?
- What if number of peers is not 2^i?
- How to prevent degeneration?
- Where to store data?



Idea: Simulate the hypercube!



Simulated Hypercube System

Simulation: Node consists of several peers! Such a hypercube can be maintained against ADV(J,L,λ)!

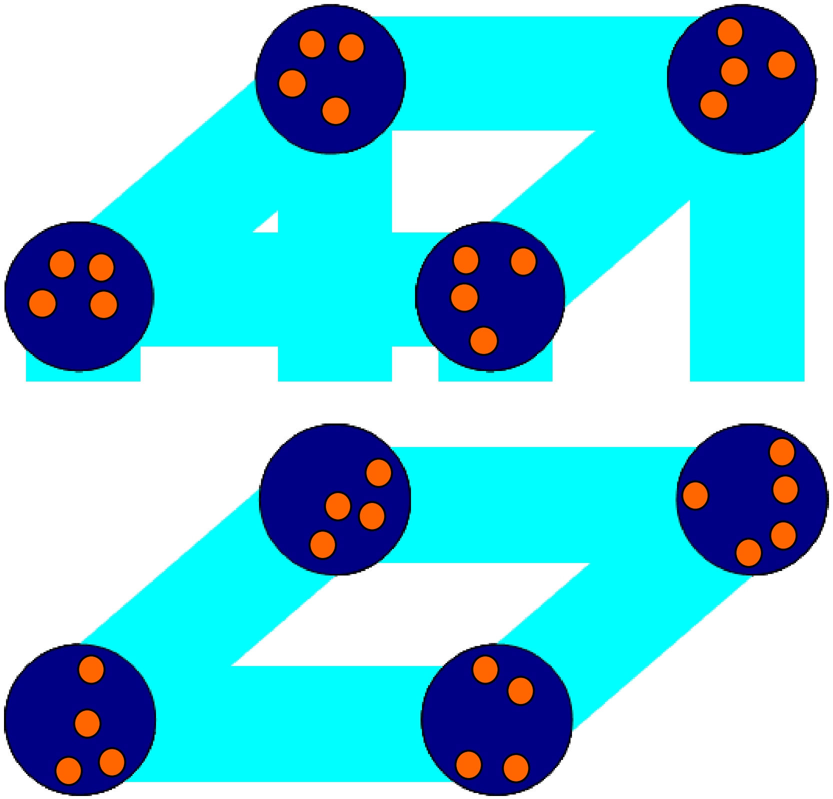
Basic components:

- Route peers to sparse areas

Token distribution algorithm!

- Adapt dimension

Information aggregation algorithm!



Components: Peer Distribution and Information Aggregation

Peer Distribution

- Goal: Distribute pee[illegible]ly among all hypercube nodes in order to balan[illegible]ed adversarial churn
- Basically a[illegible]n distribution problem

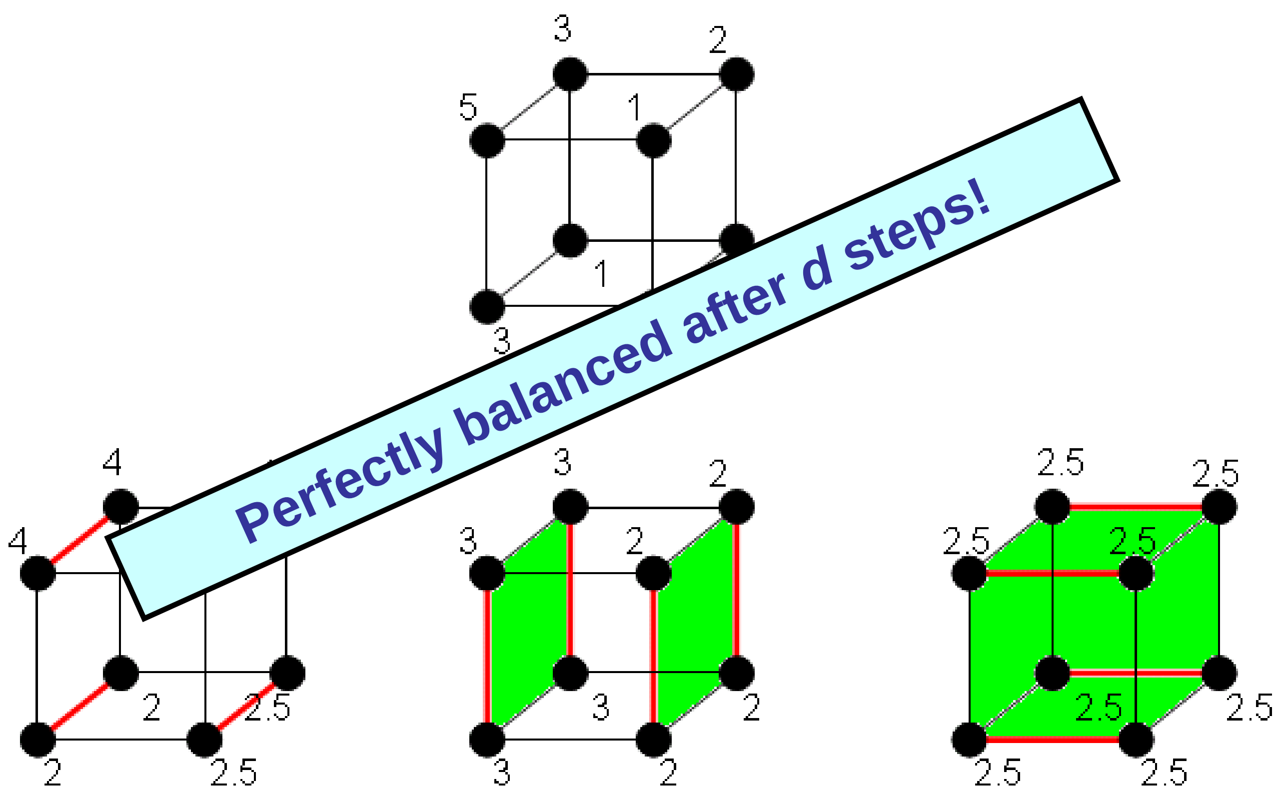
Tackled next!

Counting the total number of peers (information aggregation)

- Goal: Estimate the total number of peers in the system and adapt the dimension accordingly

Peer Distribution (1)

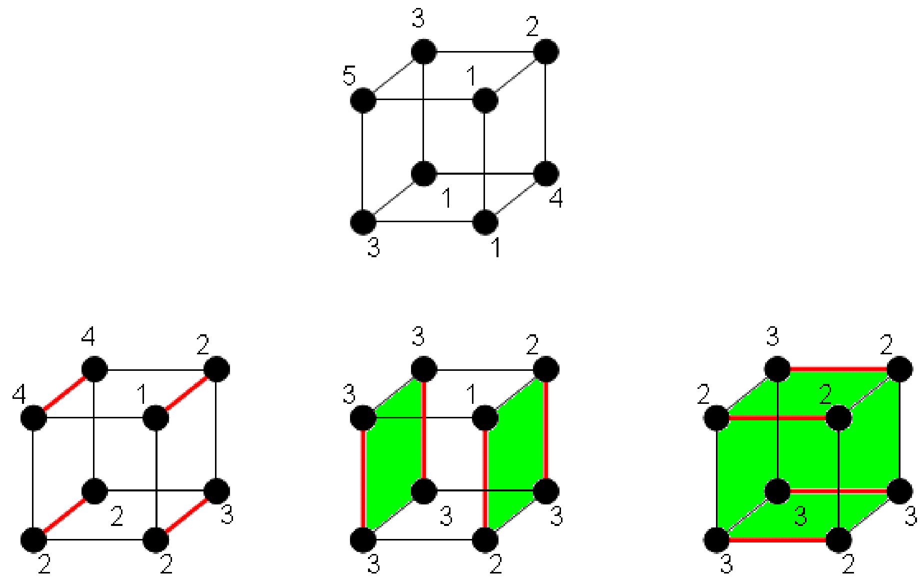
Algorithm: Cycle over dimensions and balance!



Perfectly balanced after d steps!

Peer Distribution (2)

- But peers are not fractional!



- And an adversary inserts at most *J* and removes at most *L* peers *per step*!

Theorem 1: Given adversary *ADV(J,L,1)*, discrepancy never exceeds *2J+2L+d*!

Components: Peer Distribution and Information Aggregation

Peer Distribution

- Goal: Distribute peers evenly among all hypercube nodes in order to balance biased adversarial churn
- Basically a token distribution problem

Counting the total number of (information aggregation)

- Goal: Estimate the number of peers in the system and adapt the dimension ingly

Tackled next!

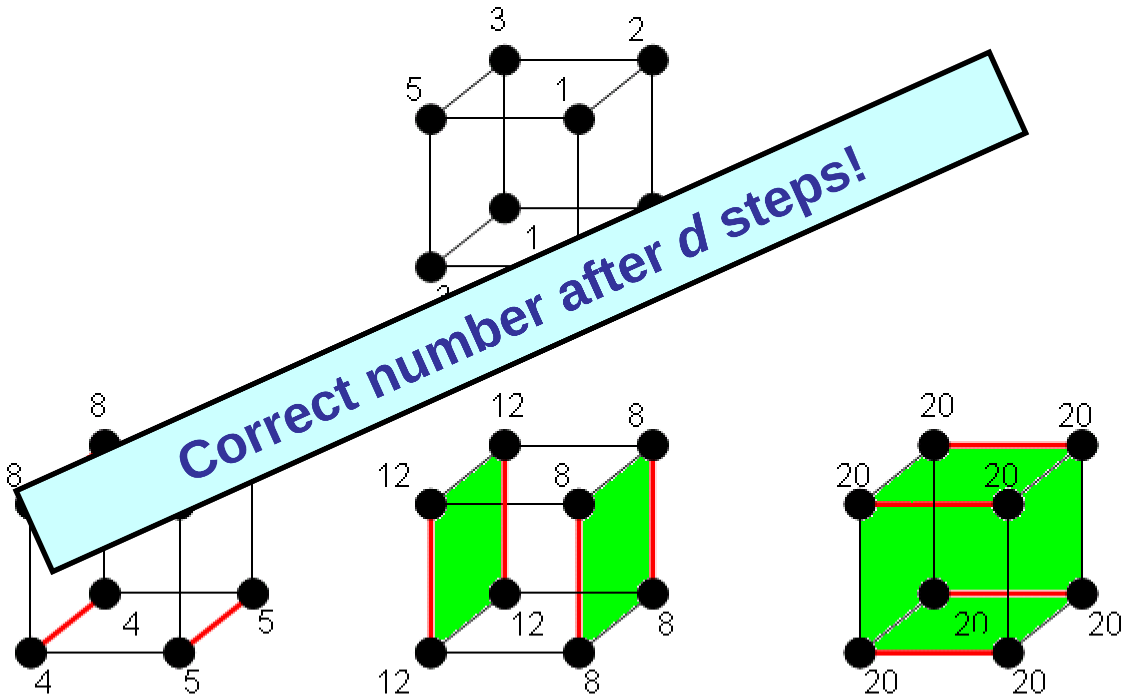
Information Aggregation (1)

- Goal: Provide the same (and good!) estimation of the total number of peers presently in the system to all nodes
  - Thresholds for expansion and reduction

- Means: Exploit again the recursive structure of the hypercube!

Information Aggregation (2)

Algorithm: Count peers in every sub-cube by exchange with corresponding neighbor!



Correct number after *d* steps!

Information Aggregation (3)

- But again, we have a concurrent adversary!
- Solution: Pipelined execution!

Theorem 2: The information aggregation algorithm yields the same estimation to all nodes. Moreover, this number represents the correct state of the system *d* steps ago!

Composing the Components

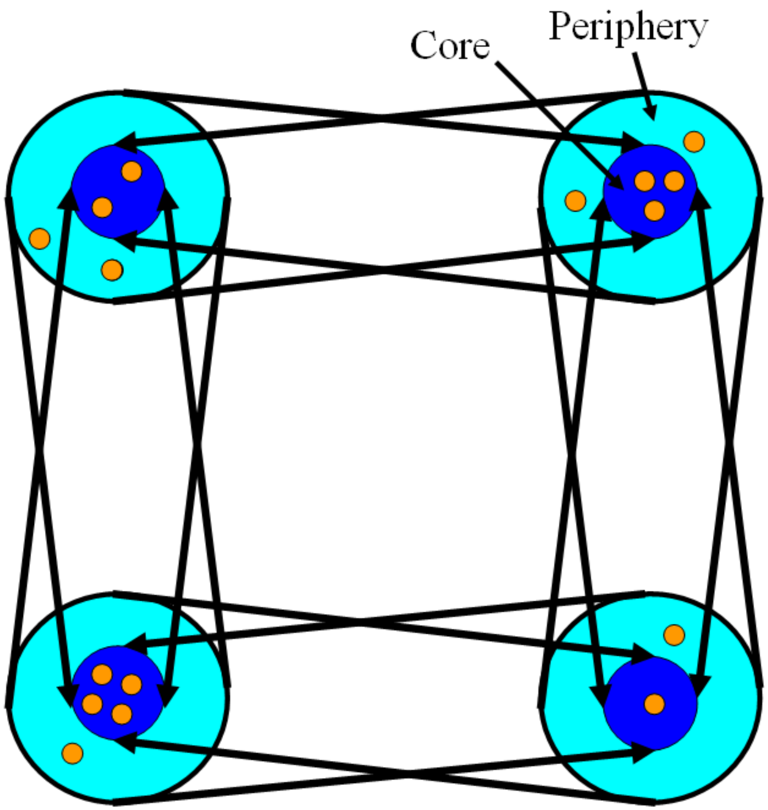
- Our system permanently runs
  - Peer distribution algorithm to balance biased churn
  - Information aggregation algorithm to estimate total number of peers and change dimension accordingly

But: How are peers connected inside a node, and how are the edges of the hypercube represented?

And: Where is the data of the DHT stored?

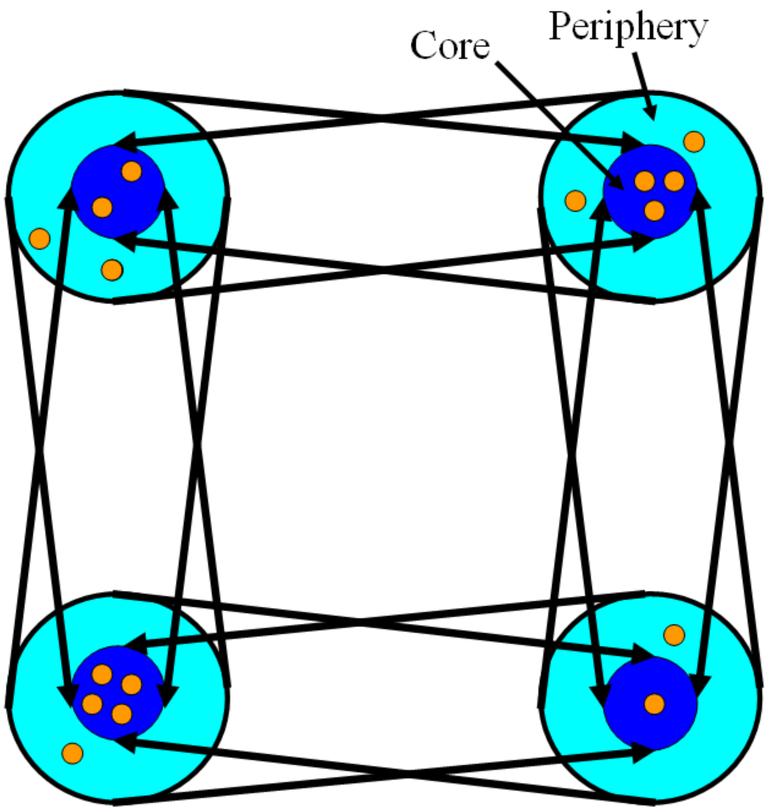
Distributed Hash Table

- Hash function determines node where data item is replicated
- Problem: Peer which has to move to another node must replace all data items.
- Idea: Divide peers of a node into core and periphery
  - Core peers store data,
  - Peripheral peers are used for peer distribution



Intra- and Interconnections

- Peers inside a node are completely connected.
- Peers are connected to all *core peers* of all neighboring nodes.
  - May be improved: Lower peer degree by using a matching.



Maintenance Algorithm

- Maintenance algorithm runs in *phases*
  - Phase = 6 rounds

- In phase *i*:
  - Snapshot of the state of the system in round 1
  - One exchange to estimate number of peers in sub-cubes (information aggregation)
  - Balances tokens in dimension *i mod d*
  - Dimension change if necessary

All based on the snapshot made in round 1, ignoring the changes that have happened in-between!

Results

- Given an adversary *ADV(d+1,d+1,6)*...
  => Peer discrepancy at most *5d+4* (Theorem 1)
  => Total number of peers with delay *d* (Theorem 2)

- ... we have, in spite of *ADV(O(log n), O(log n), 1)*:

  – always at least one core peer per node (no data lost!),

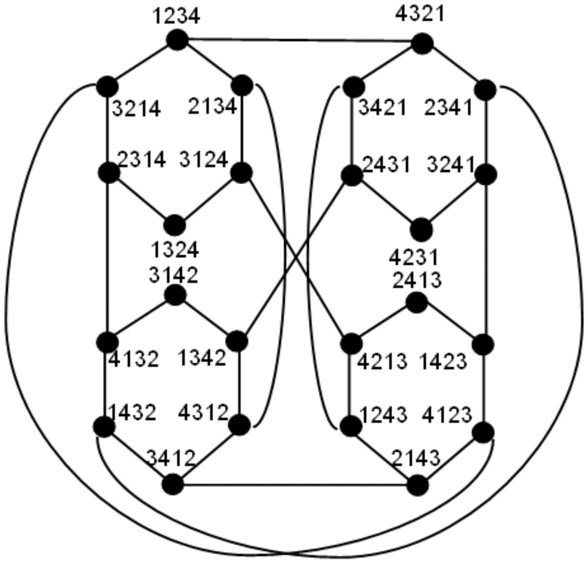
  – peer degree *O(log n)* (asymptotically optimal!),

  – network diameter *O(log n)*.

Discussion

- Simulated topology: A simple blueprint for dynamic P2P systems!
  - Requires algorithms for token distribution and information aggregation on the topology.
  - Straight-forward for skip graphs
  - Also possible for pancake graphs!

    (Diameter = Degree = O(log n / loglog n))

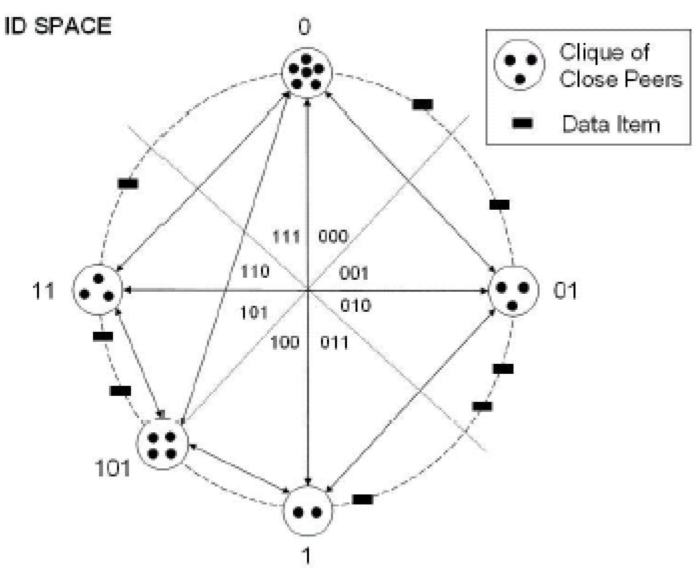


- A lot of future work!
  - A first step only: dynamics of P2P systems offer many research chellenges!
  - E.g.: Other dynamics models, self-stabilization after larger changes, etc.!
  - E.g.: Selfishness => see CHALLENGE 2
  - E.g.: also measurment studies are subject to current research:
    - Churn in file sharing systems?
    - Churn in Skype? (=> IPTPS 2006)

eQuus: An Alternative Approach with Low Stretch (1)

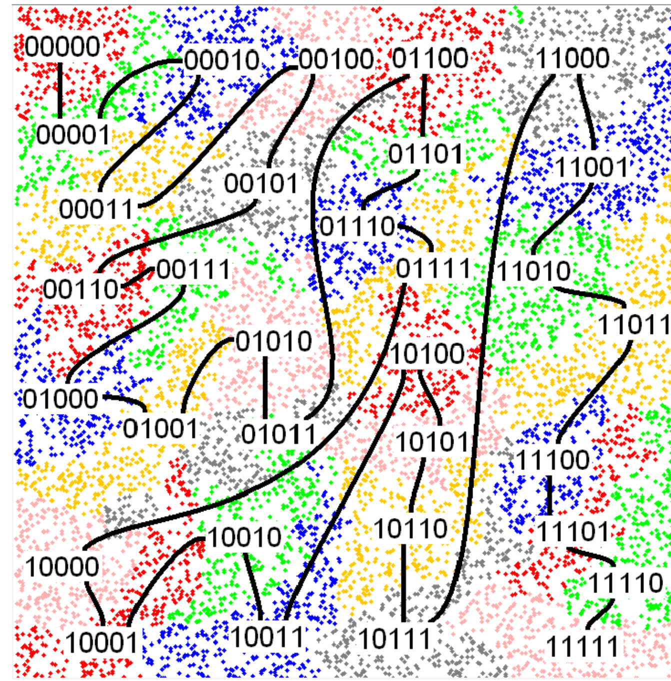
- eQuus
  - Optimized for random joins/leavs rather than worst-cae
  - Hypercube too restrictive
  - Token distribution is expensive
  - Adding locality awareness!

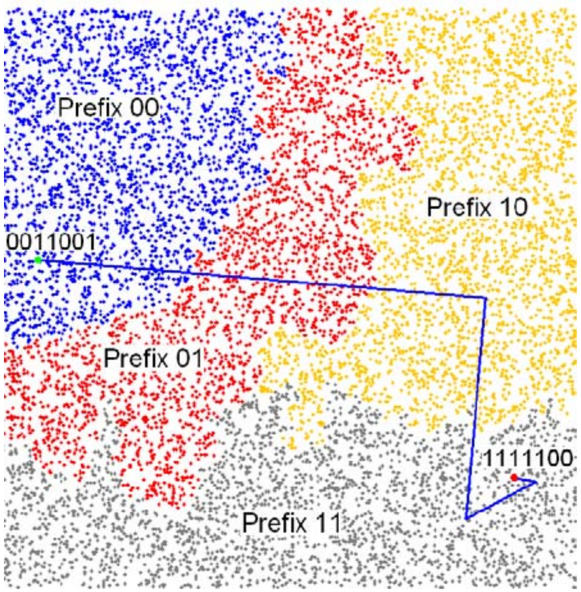
- "Simulated Chord"
  - Local split and merge only
  - According to constant thresholds
  - Split operation according to latencies!



eQuus: An Alternative Approach with Low Stretch (2)

- Split and merge happen seldom
  - If joins and leave uniformly distributed: balls-into-bins
  - Small stretches if nodes are uniformly distributed (= roughly direct paths used)





CHALLENGE 2:

Selfish Peers

Challenge 1 -> Challenge 2

- Simulated hypercube topology is fine…
- … if peers act according to protocol!
- However, in practice, peers can perform selfishly!

Motivation

Power of Peer-to-Peer Computing =

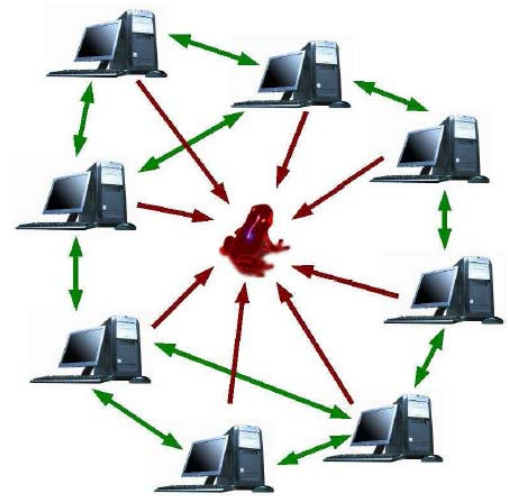
Accumulation of Resources of Individual Peers

- CPU Cycles
- Memory
- Bandwidth
- …

Collaboration is of peers is vital!

However, many free riders in practice!

Motivation



- Free riding
  - Downloading without uploading
  - Using storage of other peers without contributing own disk space
  - Etc.

- In this talk: selfish neighbor selection in unstructured P2P systems

- Goals of selfish peer:

  (1) Maintain links only to a few neighbors (small out-degree)

  (2) Small latencies to all other peers in the system (fast lookups)

What is the impact on the P2P topologies?

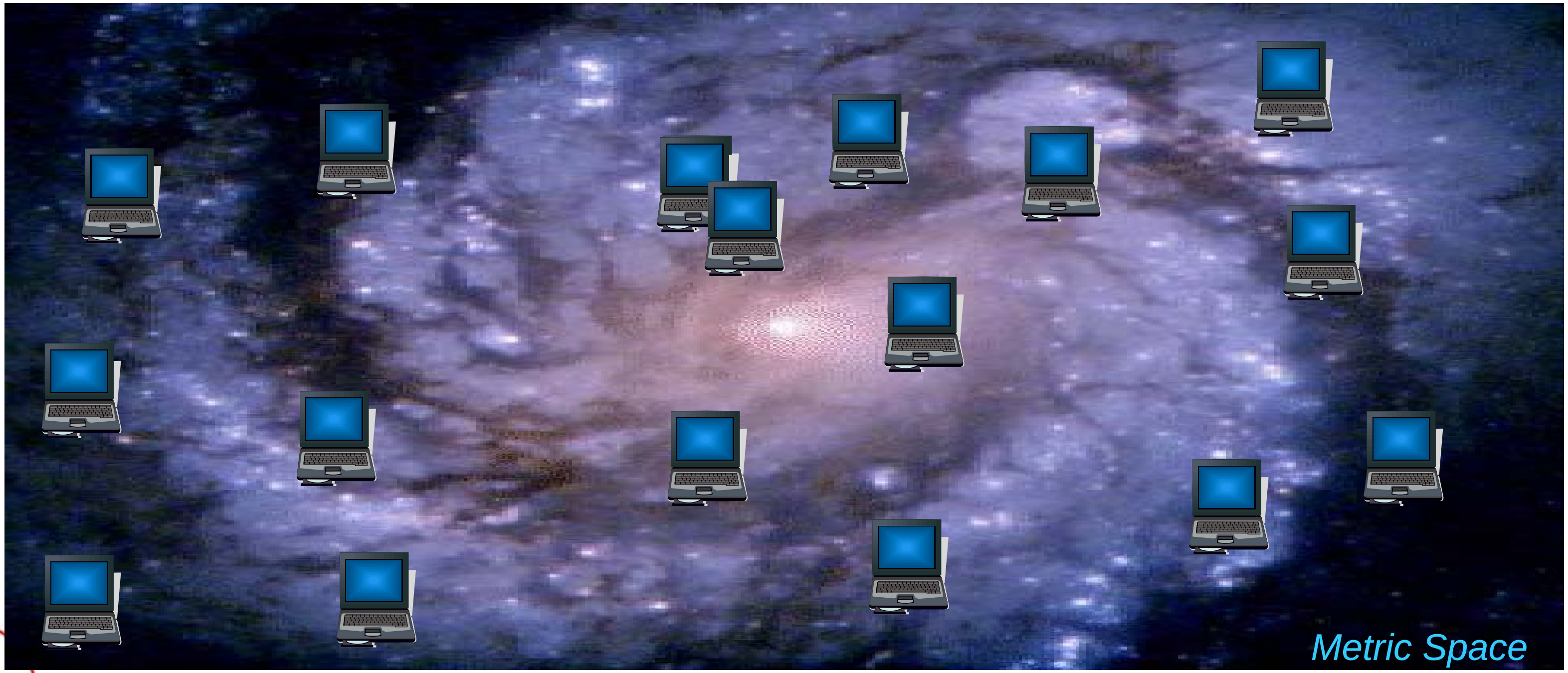
Challenge 2: Road-Map

➡ Problem statement

- Game-theoretic tools
- How good / bad are topologies formed by selfish peers?
- Stability of topologies formed by selfish peers
- Conclusion

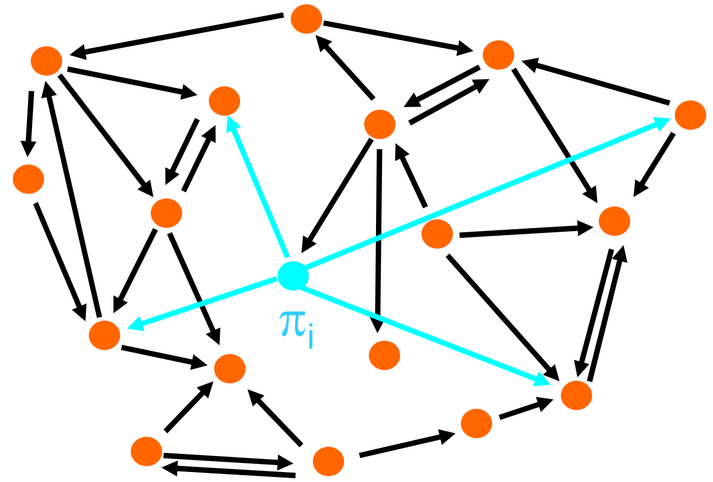
Problem Statement (1)

- n peers $\{\pi_0, \ldots, \pi_{n-1}\}$
- distributed in a metric space
  - Metric space defines distances between peers
  - triangle inequality, etc.
  - E.g., Euclidean plane



Problem Statement (2)

- Each peer can choose…
  - to which
  - and how many
  - … other peers its connects
- Yields a directed graph *G*



Problem Statement (3)

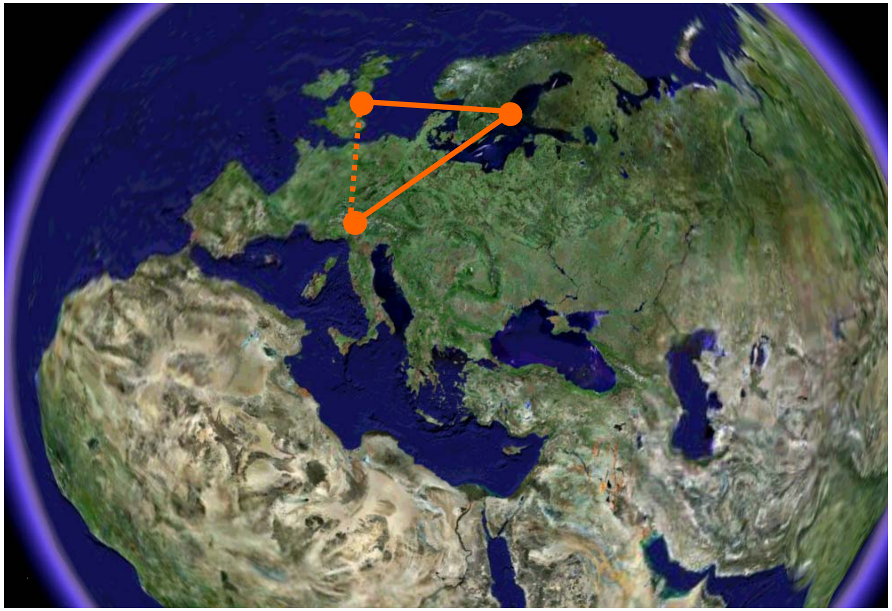
- Goal of a selfish peer:

(1) Maintain a small number of neighbors only (out-degree)

- Only little memory used
- Small maintenance overhead

(2) Small stretches to all other peers in the system

- Fast lookups!
- Shortest distance using edges of peers in G…
- … divided by shortest direct distance



Problem Statement (4)

- Cost of a peer:
  - Number of neighbors (out-degree) times a parameter α
  - plus stretches to all other peers
  - α captures the trade-off between link and stretch cost

$$\text{cost}_i = \alpha \ \text{outdeg}_i + \sum_{i \neq j} \text{stretch}_G(\pi_i, \pi_j)$$

- Goal of a peer: Minimize its cost!

Challenge 2: Road-Map

- Problem statement
- Game-theoretic tools
- How good / bad are topologies formed by selfish peers?
- Stability of topologies formed by selfish peers
- Conclusion

Game-theoretic Tools (1)

- Social Cost
  - Sum of costs of all individual peers:

$$\text{Cost} = \sum_i \text{cost}_i = \sum_i \left(\alpha \ \text{outdeg}_i + \sum_{i \neq j} \text{stretch}_G(\pi_i, \pi_j)\right)$$

- Social Optimum OPT
  - Topology with minimal social cost of a given problem instance
  - => “topology formed by collaborating peers”!

What topologies do selfish peers form?

=> Concepts of Nash equilibrium and Price of Anarchy

Game-theoretic Tools (2)

- Nash equilibrium
  - “Result” of selfish behavior => “topology formed by selfish peers”
  - Topology in which no peer can reduce its costs by changing its neighbor set
  - In the following, let NASH be social cost of worst equilibrium
- Price of Anarchy
  - Captures the impact of selfish behavior by comparison with optimal solution
  - Formally: social costs of worst Nash equilibrium divided by optimal social cost

$$PoA = \max_I \{NASH(I) / OPT(I)\}$$

Challenge 2: Road-Map

- Problem statement
- ➡ Game-theoretic tools
- How good / bad are topologies formed by selfish peers?
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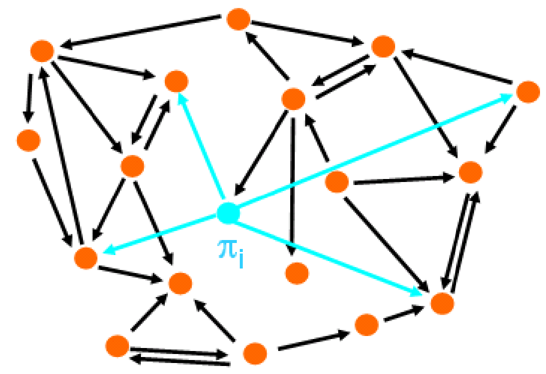
Analysis: Social Optimum

- For connectivity, at least *n* links are necessary
  - => OPT $\geq \alpha$ n
- Each peer has at least stretch 1 to all other peers
  - => OPT $\geq$ n · (n-1) · 1 = $\Omega(n^2)$

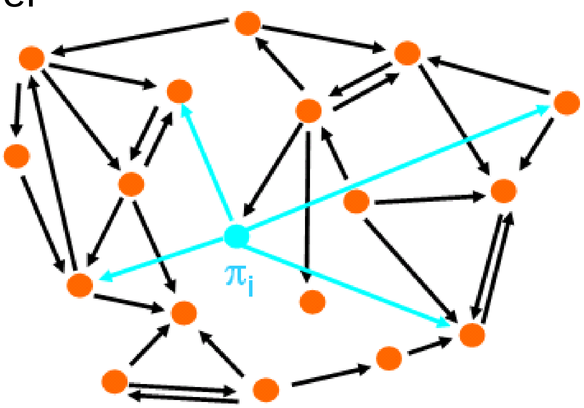


Theorem: Optimal social costs are at least

OPT $\in \Omega(\alpha$ n + n$^2)$

Analysis: Social Cost of Nash Equilibria

- In any Nash equilibrium, no stretch exceeds α+1
  - Otherwise, it's worth connecting to the corresponding peer
  - Holds for any metric space!



- A peer can connect to at most *n*-1 other peers

- Thus: $\text{cost}_i \leq \alpha\, O(n) + (\alpha+1)\, O(n)$

  => social cost $\text{Cost} \in O(\alpha\, n^2)$

Theorem:

In any metric space, NASH $\in O(\alpha\, n^2)$

Analysis: Price of Anarchy (Upper Bound)

- Since OPT = $\Omega(\alpha\ n + n^2)$ ...
- … and since NASH = $O(\alpha\ n^2)$,
- we have the following upper bound for the price of anarchy:

Theorem:

In any metric space, PoA $\in O(\min\{\alpha, n\})$.

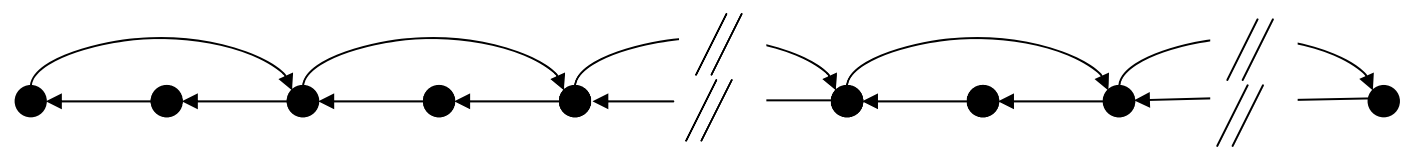
Analysis: Price of Anarchy (Lower Bound) (1)

- Price of anarchy is tight, i.e., it also holds that

Theorem: The price of anarchy is

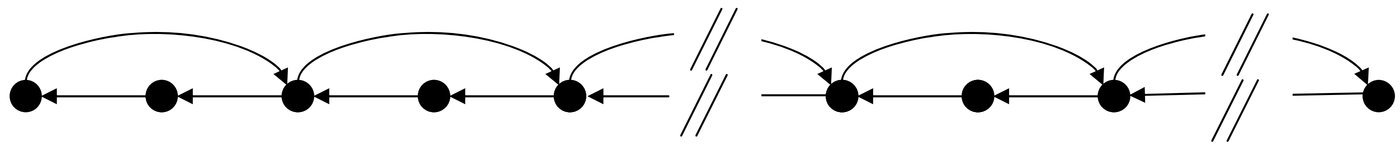
PoA $\in \Omega(\min\{\alpha, n\})$

- This is already true in a 1-dimensional Euclidean space:



Peer:	π_1	π_2	π_3	π_4	π_5	…	π_{i-1}	π_i	π_{i+1}	…	π_n
Position:	$\frac{1}{2}$	α	$\frac{1}{2}\alpha^2$	α^3	$\frac{1}{2}\alpha^4$	…	$\frac{1}{2}\alpha^{i-2}$	α^{i-1}	$\frac{1}{2}\alpha^i$	…	$\frac{1}{2}\alpha^{n-1}$

Price of Anarchy: Lower Bound (2)



Peer:	π_1	π_2	π_3	π_4	π_5	…	π_{i-1}	π_i	π_{i+1}	…	π_n
Position:	½	α	½ α^2	α^3	½ α^4	…	½ α^{i-2}	α^{i-1}	½ α^i	…	½ α^{n-1}

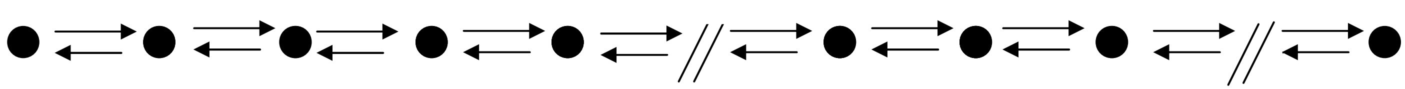
To prove:

(1) "is a selfish topology" = instance forms a Nash equilibrium

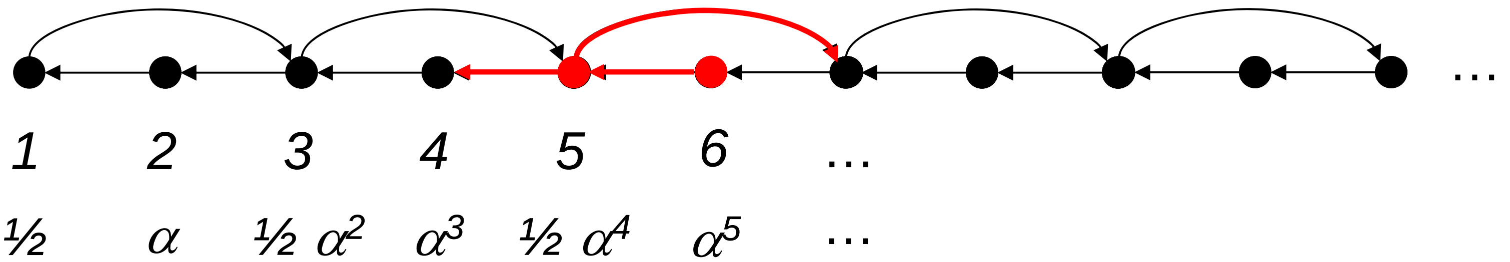
(2) "has large costs compared to OPT"

= the social cost of this instance is $\Theta(\alpha\ n^2)$

Note: Social optimum is at most $O(\alpha\ n + n^2)$:



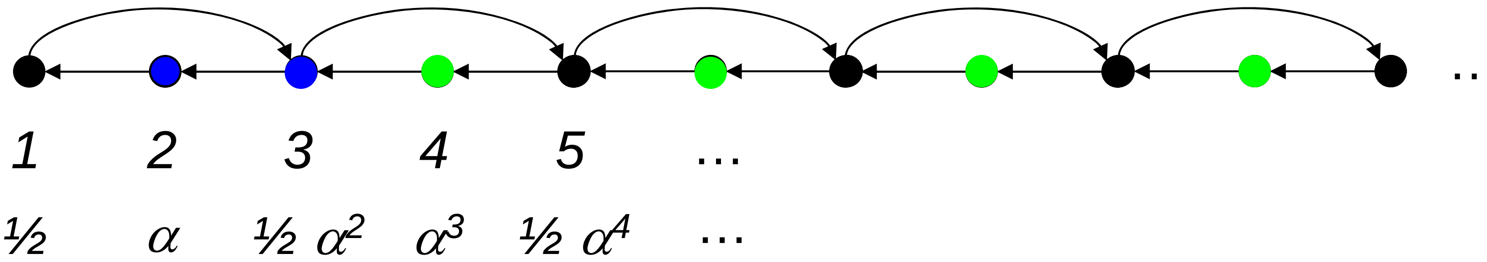
Price of Anarchy: Lower Bound (3)



- Proof Sketch: Nash?
  - Even peers:
    - For connectivity, at least one link to a peer on the left is needed
    - With this link, all peers on the left can be reached with an optimal stretch 1
    - No link to the right can reduce the stretch costs to other peers by more than α
  - Odd peers:
    - For connectivity, at least one link to a peer on the left is needed
    - With this link, all peers on the left can be reached with an optimal stretch 1
    - Moreover, it can be shown that all alternative or additional links to the right entail larger costs

Price of Anarchy: Lower Bound (4)

- Idea why social cost are $\Theta(\alpha\ n^2)$: $\Theta(n^2)$ stretches of size $\Theta(\alpha)$



- The stretches from all odd peers *i* to a even peers *j>i* have stretch > $\alpha/2$

- And also the stretches between even peer *i* and even peer *j>i are* > $\alpha/2$

Price of Anarchy

Theorem: The price of anarchy is

PoA $\in \Theta(\min\{\alpha, n\})$

- PoA can grow linearly in the total number of peers
- PoA can grow linearly in the relative importance of degree costs α

Challenge 2: Road-Map

- Problem statement
- Game-theoretic tools
- How good / bad are topologies formed by selfish peers?
- Stability of topologies formed by selfish peers
- Conclusion

Stability (1)

- Peers change their neighbors to improve their individual costs.

How long thus it take until no peer has an incentive to change its neighbors anymore?

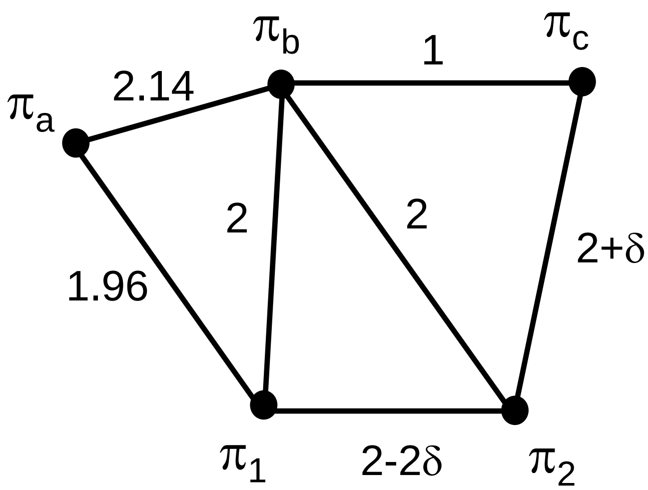
Theorem:

Even in the absence of churn, peer mobility or other sources of dynamism, the system may never stabilize (i.e., P2P system never reaches a pure Nash equilibrium)!

Stability (2)

- Example for α=0.6

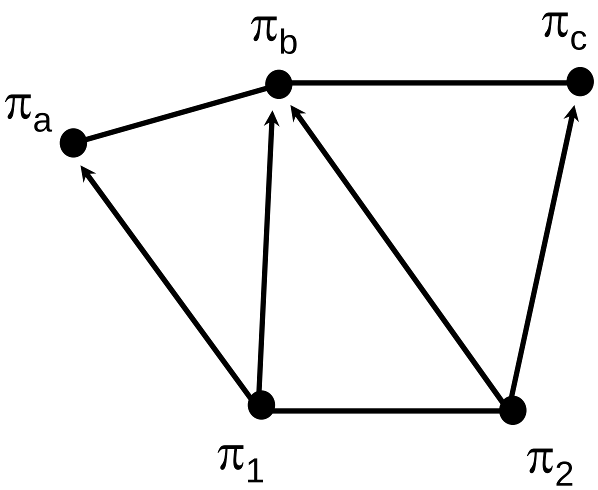
- Euclidean plane:



δ…arbitrary small number

Stability (3)

- Example sequence:

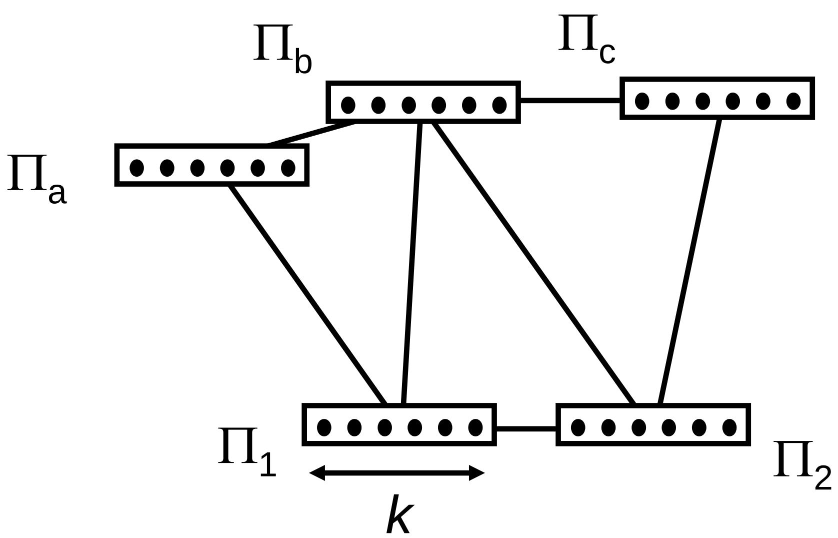


Again initial situation
=> Changes repeat forever!

- Generally, it can be shown that there is no set of links for this instance where no peer has an incentive to change.

Stability (4)

- So far: no Nash equilibrium for α=0.6
- But example can be extended for α of all magnitudes:
  - Replace single peers by group of k=n/5 very close peers on a line
  - No pure Nash equilibrium for α=0.6k



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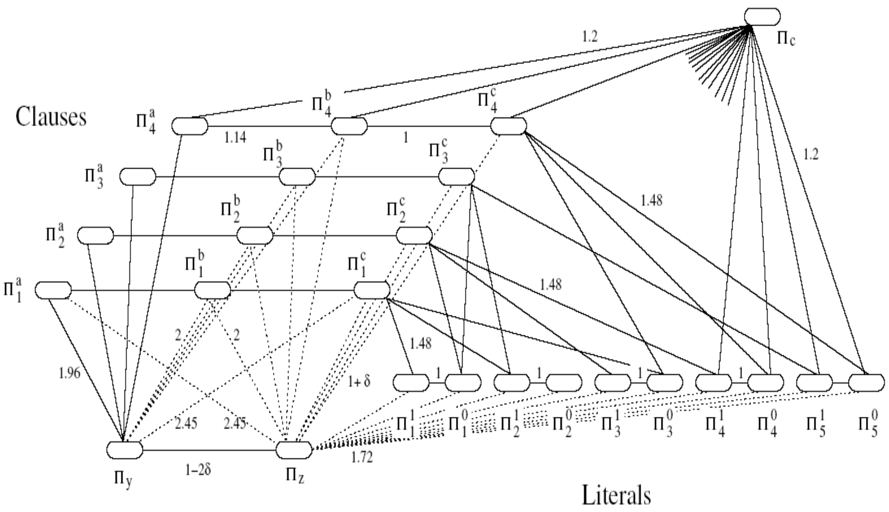
Conclusion

- Unstructured topologies created by selfish peers
- Efficiency of topology deteriorates linearly in the relative importance of links compared to stretch costs, and in the number of peers
- Instable even in static environments
- Future Work:
  - Complexity of stability? NP-hard!
  - Routing or congestion aspects?
  - Other forms of selfish behavior?
  - More local view of peers?
  - Mechanism design?



Thank you for your attention!

Questions? Comments?

Further reading:

1. “A Self-repairing Peer-to-Peer System Resilient to Dynamic Adversarial Churn”, Kuhn, Schmid, Wattenhofer; *Ithaca, New York, USA, IPTPS 2005.*
2. “On the Topologies Formed by Selfish Peers”, Moscibroda, Schmid, Wattenhofer; *Santa Barbara, California, USA, IPTPS 2006.*
3. “eQuus – A Provably Robust and Efficient Peer-to-Peer System”, Locher, Schmid, Wattenhofer; *submitted*.