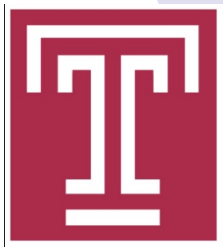
Uncovering the Useful Structures of Complex Networks in a Socially-Rich and Dynamic Environment



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Complex Networks

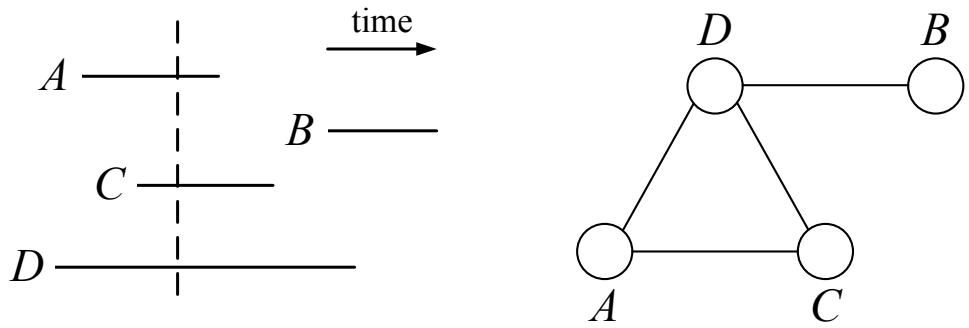
- A complex network (CN) is applicable in many fields
  - Internet, food web, metabolic networks, and social networks
  - CN in socially-rich and dynamic environments
- Three challenging areas
  - Graph model
  - Uncovering a useful structure
  - Distributed and localized solutions
- Different communities
  - Graph theory, distributed systems (e.g., ICDCS), distributed computing (e.g., PODC), and social networks

Graph Model

- Dynamics of CN: node connections change over time, e.g., DTN

Which graph model is suitable for representing a CN?

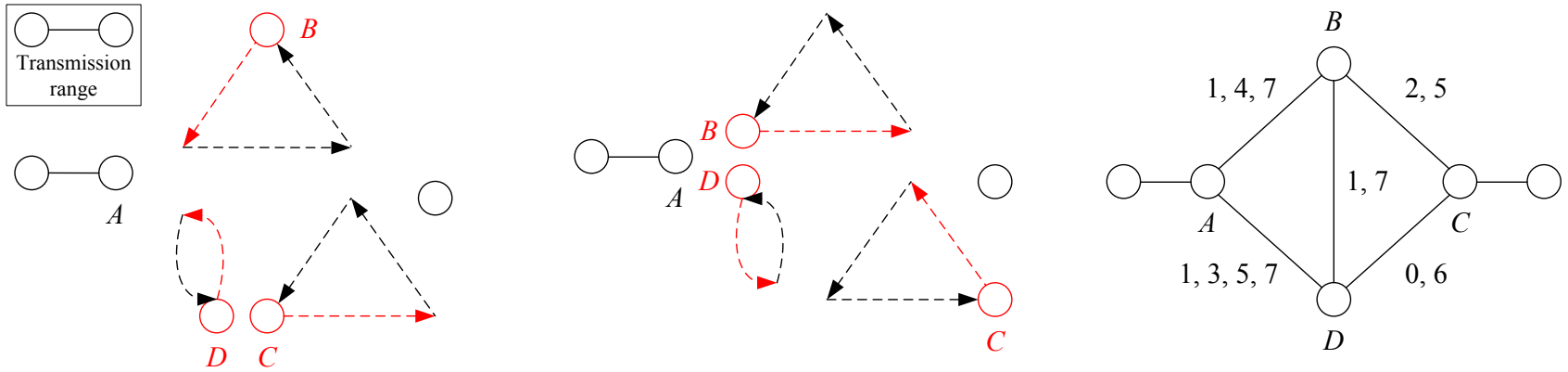
- Intersection graphs: unit disk graphs and interval graphs



- Challenges
  - Hyperedge (ACD in above): a link connecting > 2 vertices
  - Interval hypergraphs and multiple interval graphs?
  - Edge density distributions in online social networks?

Graph Model (cont'd)

- Time-evolving graph (EG) in (discrete) time and space



- EG extends to temporal with new notion of connectivity
  - Path to journey (a path over time)
  - Diameter to dynamic diameter (flooding time)
  - Earliest completion path, fastest path, minimum hop path
- Challenges
  - Macro-level vs. micro-level (probabilistic contact, edge-Markovian)
  - Granularity control: expressiveness vs. decision power

Uncovering Useful Structure

- Structural trimming: trim "useless" nodes and links
  - Static vs. dynamic, e.g., connected dominating set (CDS)
- Challenges
  - Dynamic trimming in EG with probabilistic contacts

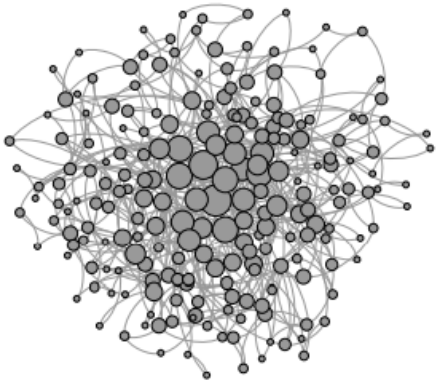
    Optimal routing, e.g., multi-bus riding
- Forwarding set (FS)
  - A single-copy message is forwarded to a new contact if it belongs to the FS.

How can we design a methodology to derive an FS?

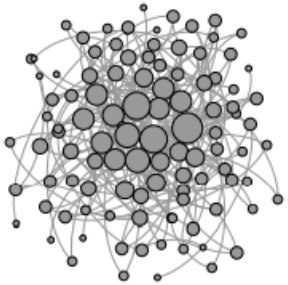
  - If message utility is time-sensitive, FS is time-varying.
  - In a multi-message deliver application, FS is copy-varying.

Uncovering Useful Structure (cont'd)

- Structural layering
  - Scale-free (SF): node degree distribution follows power-law
  - Nested SF: SF hierarchy is done by peeling off lowest degree nodes. All subsequent subgraphs are SF and "similar."



(a) P2P network with all peers.



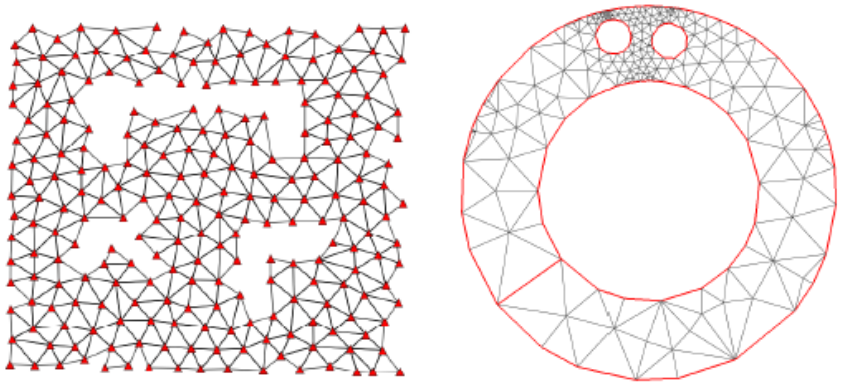
(b) Top 50% peers.

Can we uncover more inherently layered structures, not only in the space dimension, but also in time-and-space?

e.g., small-world behavior of the real world in time-and-space

Uncovering Useful Structure (cont'd)

- Structural remapping: representation
  - Geographic routing: conformal mapping using Ricci flow
  - Greedy routing without being stuck at a local minimum



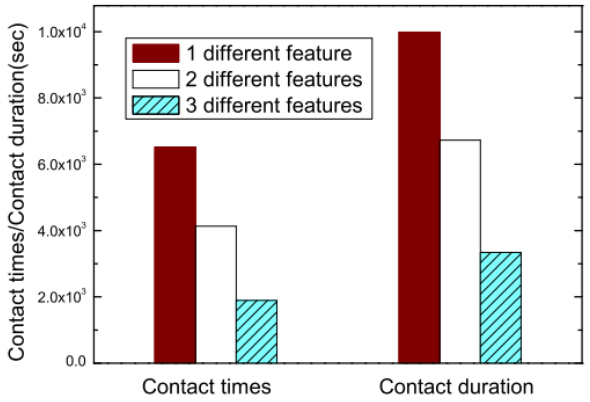
(a) Graph with non-convex holes. (b) Virtual coordinate map.

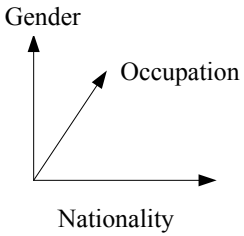
  - Mapping from one representation to another: Euclidean space to non-Euclidean space

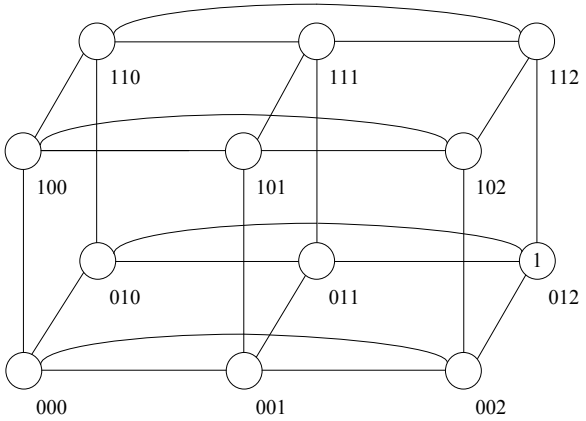
Can we remap a problem from one domain to another?

Uncovering Useful Structure (cont'd)

- Structural remapping: domain
  - Converting a routing in a highly mobile and unstructured contact space in DTN to one in a static and structured feature space





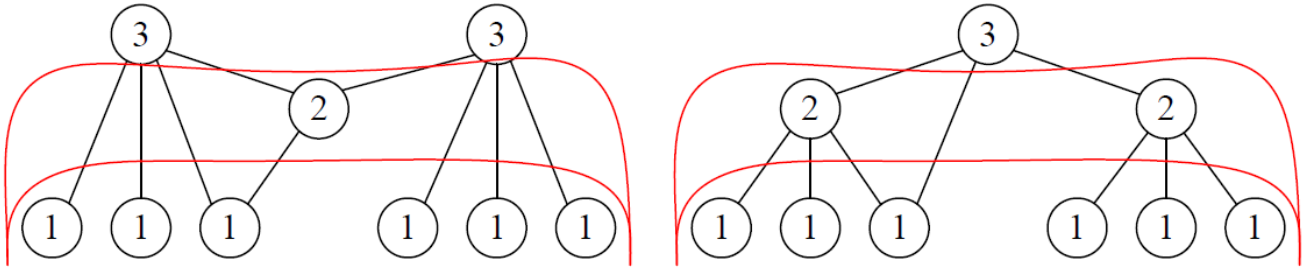


How can we uncover the influence that social relationships have on the structure of an underlying network?

Multi-scale and multi-layer CNs

Distributed/Localized Solutions

- Static labels: each node is labeled a small number of times
  - E.g., clustering, maximum independent set (MIS), CDS
- Nested SF (single root) vs. regular SF (multiple roots)

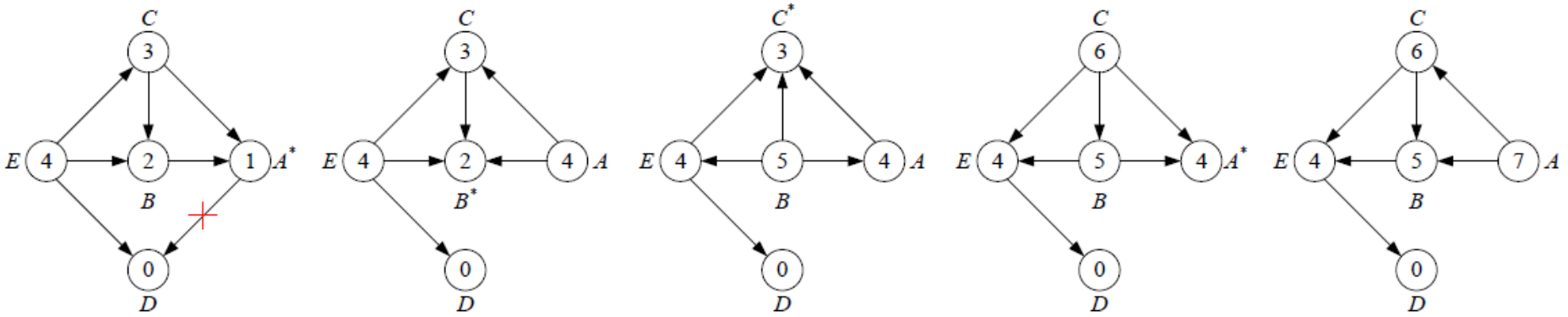


(a) Node degree (b) Nested node degree

Up-and-down routing

Distributed/Localized Solutions (cont'd)

- Dynamic labels: a labeling process where nodes are labeled a large number of times
  - E.g., Bellmen-Ford algorithm, Page Rank, and HITS
- Link reversal (LR): labels associated with nodes as height
  - Maintaining a destination-oriented DAG upon link failures



(a) Reversal at A. (b) Reversal at B. (c) Reversal at C. (d) Reversal at A again. (e) Destination-oriented DAG.

Special LR with labels associated with links, still $O(n^2)$

Distributed/Localized Solutions (cont'd)

- Type of solutions
  - Distributed solution (DS): a node's interaction with others in a restricted vicinity, say k-hop; maintaining and propagating labels
  - Localized solution (LS): DS without information propagation
- Challenges:

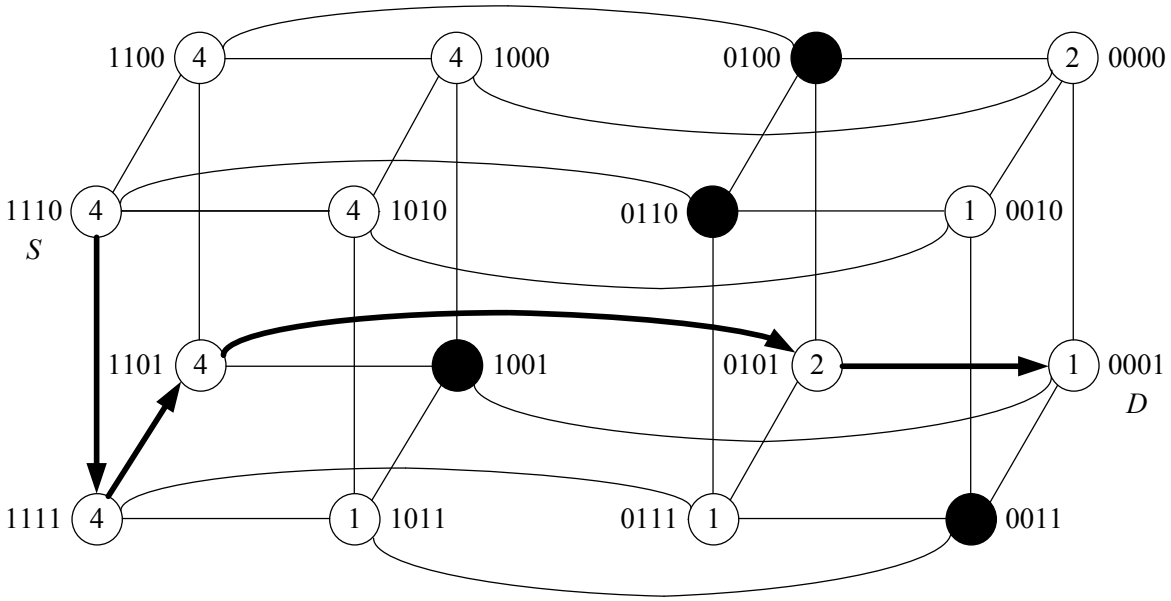
How can we deal with the complexity of building a structure along with a change of topology?

  - View consistency: SDN (central) vs. MANET (distributed)

How do we handle the long convergence time usually occurred in the dynamic label in a distributed solution?

Distributed/Localized Solutions (cont'd)

- Hybrid of distributed and localized
  - E.g., Fault-tolerant routing and broadcasting in hypercubes



- Safety levels: special coded labels
  - Unlike LR, safety level is decided, at most, once. Overall, O(log n)

Conclusions

Several key issues in complex networks

- Graph model
  - Intersection graphs: unit disk graph and interval graph
  - Time-evolving graphs
- Building a useful structure
  - Trimming, layering, and remapping
- Challenges in designing distributed/localized solutions
  - Static labels and dynamic labels
  - Hybrid of distributed and localized