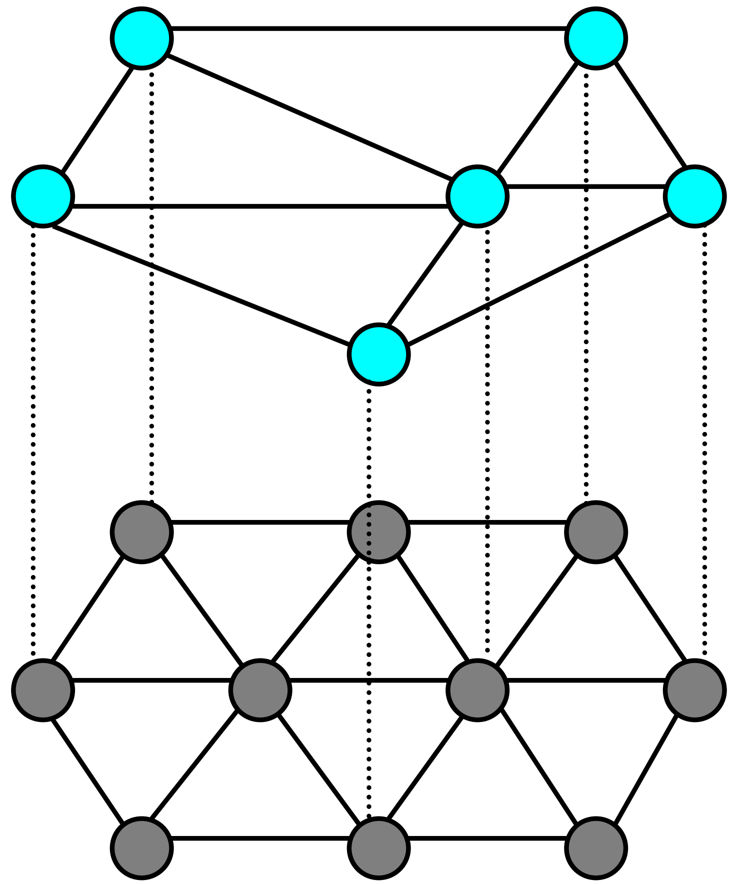
Ossification of the Internet

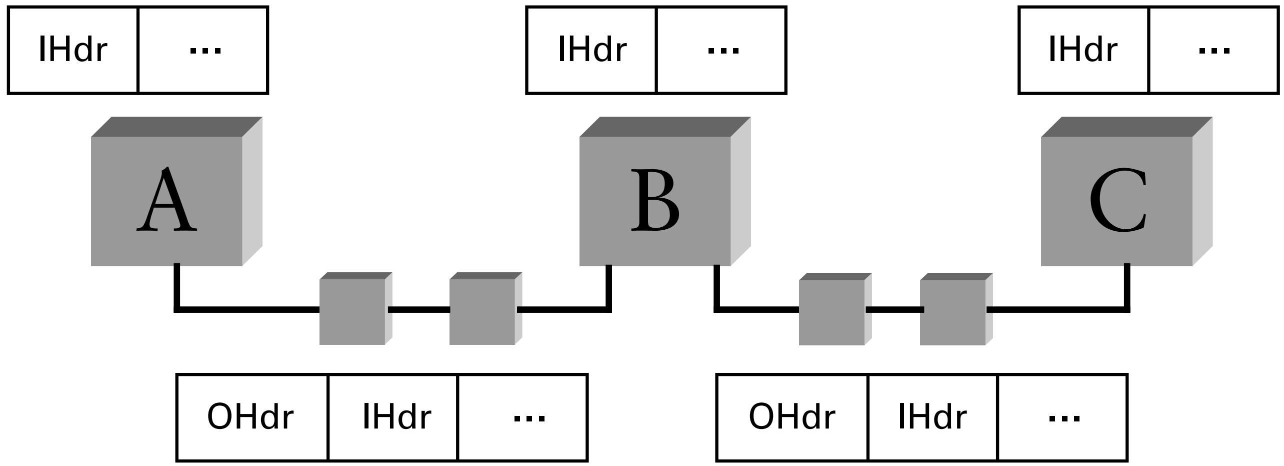
- **The Internet evolved as an experimental packet-switched network**
- **Today, many aspects appear to be "set in stone"**
  - Witness difficulty in getting IP multicast deployed
  - Major obstacles to deployment of IPv6
- **Yet many reasons to extend the Internet**
  - E.g., BGP doesn't even try to find optimal routes
  - Want extensions to routing—multicast, anycast, . . .
  - Might want greater availability than on Internet
- **But can only change end nodes, not routers**

Solution: Overlays

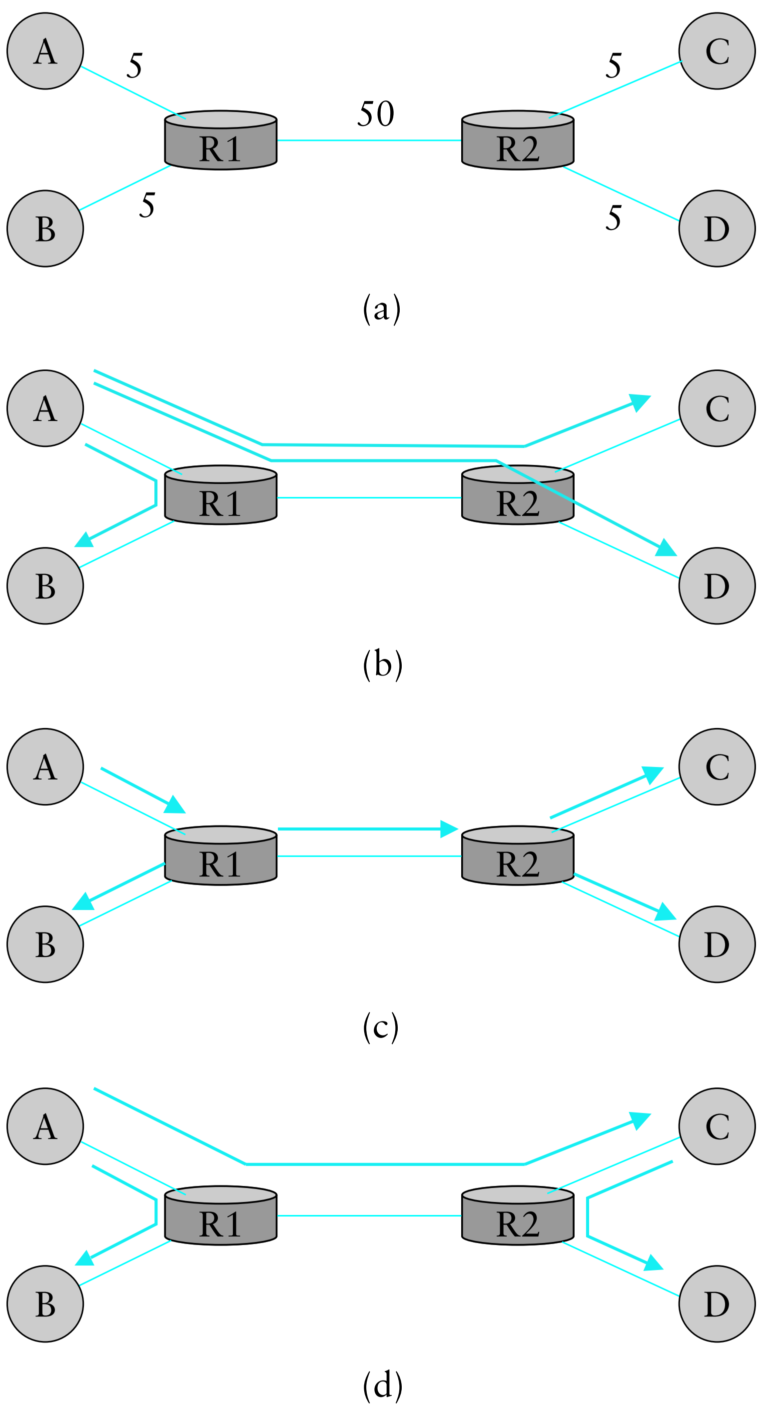


- **Use Internet to form "virtual links"**
- **Build your own network on top of Internet**
  - E.g., RON project greatly increases availability

Tunnels



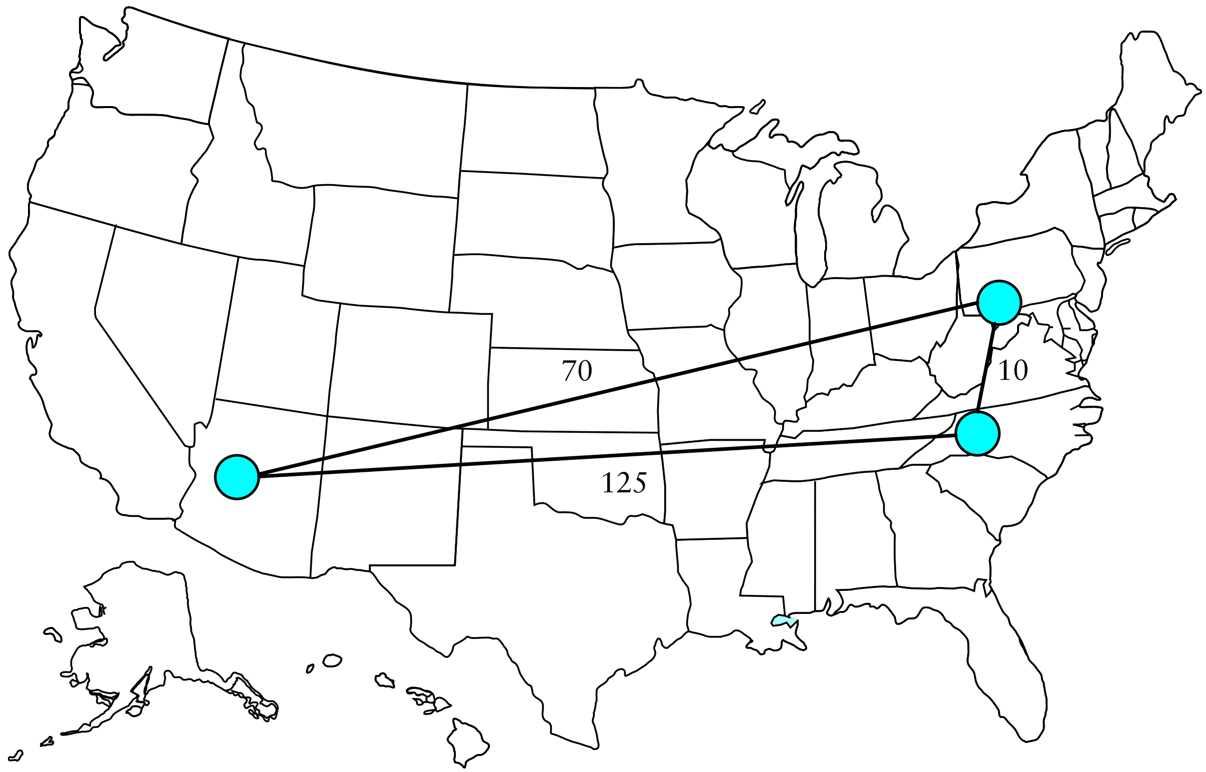
- **Use tunnels to form virtual links**
  - Encapsulate your network packets in IP datagrams
- **Examples:**
  - IPv6-in-IPv4 packets
  - Mbone overlays
  - End-system multicast
- **How to select links?**



Overlay choice

- **Consider topology (a)**
  - Naive solution is iterated unicast from source (b)—suboptimal
  - Optimal requires router support (c)
  - Best overlay would be (d)
- **How to select links?**
  - Use standard routing protocol (DVMRP)
  - Want something close to underlying Internet topology
  - But must estimate link costs by measurement

Triangle inequality



- **Want to use links that will improve performance**
- **Triangle equality holds often, but not always**
  - I.e., Latencies $(a \to b) \not\leq (a \to c) + (c \to a)$

Example overlay construction

- **View overlay as a mesh embedded in Internet**
  - Standard routing protocol selects routes in overlay
- **Add edges whenever a node joins**
  - Join means adding edges to one or more existing nodes
- **Add edges after failure, or to improve optimality**
  - i periodically probes random node j
  - Add link $i \leftrightarrow j$ if sufficiently utility: $\sum_{m \neq i} \left(\frac{\Delta \text{ latency w. } i \leftrightarrow j}{\text{latency without}} \right)$
- **Remove based on Cost**
  - $\max(\text{\# routes w. } i \to j \text{ as first hop}, \text{\# w. } j \to i)$

Peer-to-peer networks

- **Aims to use the bandwidth and storage of the many hosts**
  - Sum of access line speeds and disk space
- **But to use this collection of machines effectively requires coordination on a massive scale**
  - Key challenge: who has the content you are looking for?
- **Moreover, the hosts are very flaky**
  - Behind slow links
  - Often connected only a few minutes
  - So system must be very robust

Napster

- **Centralized search engine:**
  - All hosts with songs register them with central site
  - Users do keyword search on site to find desired song
  - Site then lists the hosts that have the song
  - User then downloads content
- **What makes this work?**
  - Central site only has to handle searches: little bandwidth
  - Vast collection of hosts can supply huge aggregate bandwidth
  - System is self-scaling: more users means more resources

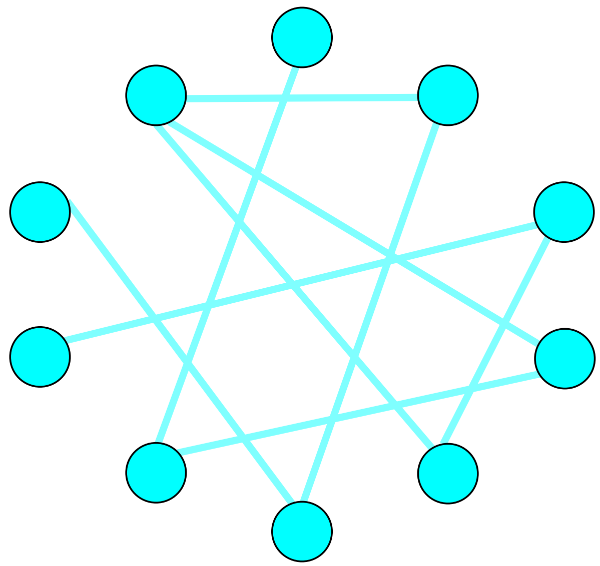
What happened to Napster?

- **Fastest growing Internet application ever**
  - P2P traffic became, and remains, one of the biggest sources of traffic on the Internet!
- **But legal issues shut site down**
- **Centralized system was vulnerable to legal attacks, and system couldn't function without central site**
  - Central point of failure
- **What can one do without a central site?**
  - That's the hard question in peer-to-peer

Gnutella

- **An example of an unstructured, decentralized P2P system**
- **Context:**
  - Many hosts join a system
  - Each offers to share its own content
  - In return, each can make queries for others content
- **Goal:**
  - Enable users to find desired content on other
  - Replaces centralized Napster DB with decentralized search

Gnutella approach



- **Step one: form an overlay network**
  - Each host, when it joins, “connects” to several Gnutella members
  - An “overlay” link is merely the fact that the nodes know each other’s IP address, and thus can send each other packets

Gnutella searches

- **Step two: search with *flood queries***
- **Each query is flooded within some scope**
  - Queries are typically keyword searches
  - TTL is used to limit scope of flood
  - Flooding means you don't need any routing infrastructure beyond links
- **All responses to queries are forwarded back along path query came from**
  - Nodes remember queries they have seen
  - Avoids duplicating queries, offers some privacy

Gnutella performance

- **Tradeoff: Accuracy vs. cost of queries**
  - if TTL is small, then searches won't find desired content
  - if TTL is large, network will get overloaded
- **Supernode optimization:**
  - Normal nodes attach to supernodes, who search for them
  - Only flood among well-connected supernodes
- **Random-walk instead of flooding optimization:**
  - Provides correct TTL automatically
- **Proactive replication**
  - Replicate content that is frequently queried, to make it easier to find

“Unstructured Overlay”

- **Gnutella is unstructured in two senses:**
  - Links between nodes are essentially random
  - The content of each node is random (at least from the perspective of Gnutella)
- **Implications:**
  - Can’t route on Gnutella
  - Wouldn’t know where to route even if we could

Structured overlays

- **Most Gnutella downloads are for widely-replicated content**
  - I.e.g, Gnutella is good at finding the "hay"
  - But how would you find "needles"?
- **Need *structured* overlays**
  - Say you know name of object
  - And only one copy of object in the system
  - Can you index object such than anyone can find it?
- **Want to lookup up name → value mapping**
  - Sounds like a hash table