Distributed Systems

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Shortest (least weight) paths with BFS tree and edge weights

- Bellman-Ford algorithm
- Each node p has a variable *dist* representing distance to root. Initially p.*dist* $=\infty$, root.*dist* = *0*
- In each round, each node sends its *dist* to all neighbors
- If for neighbor q of p: q.*dist* + w(p,q) < p.*dist*
  - Then set p.*dist* = q.*dist* + w(p,q)

Shortest (least weight) paths with BFS tree and edge weights

- Complexity
  - (when all edge weights are positive)
  - Time: n-1 ≈ O(n)
  - Message: O(n*|E|)

- Also works for directed graphs

Weighed diameter

- In a weighted graph, the weighted diameter or weight-diameter is the
- Largest weight of the least weight path between 2 nodes

Bit complexity of communicaiton

- We have assumed that each communication is 1 message, and we counted the messages
- Sometimes, communication is evaluated by bit complexity – the number of bits communicated
- This is different from message complexity because a message may have number of bits that depend on n or |E| or Diameter

- For example, A routing table may be sent in a message, and a routing table has size O(n)

- In practice, data of size O(log n) can be assumed to fit in a single message. E.g. node id
- Data of size polynomial of n: O(n), O(√n) etc need corresponding message sizes

Distributed Systems

Systems and models

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Models

- Assumptions we make about the system
- Necessary to reason about systems

- Real world is too elaborate, too detailed

- We must discard unnecessary details and focus on the essentials
- Sometimes we may not know details in advance, when designing the system.
  - Our design must be general enough that they do not depend on these details

Models

- No one right way to model
- Always depends on the system and application in question
- Very often we do not know exactly where our design will be used
  - Try to make worst case assumptions that still give reasonable performance
- Today we discuss some elements of distributed systems that must be modeled, and some common aspects to keep in mind

Things to model

- Hardware
- Energy
- Communication
- Architecture: How software components are related
- Failures
- Computation
- Time and synchronization
- Security
- Mobility

Hardware

- Heterogeneity: Different nodes may have different properties
  - Speed of CPU
  - Memory
  - Storage
  - Polynomial of n memory/storage can be problematic
  - We can:
    - Try to model a few different types of nodes, specially when we know exactly which nodes will be of what type. E.g. Hand built cluster for a specific purpose
    - Or we can assume all nodes to be low power. E.g. sensor networks
  - In general, try to keep computation, memory and storage requirement *per node* as low as possible

Energy

- Important to prevent heating and to save battery
- Computation and communication cost energy
- In data centers processing "big data"
  - Keeping consumption low is critical
  - To keep down energy costs
  - To keep heating under control
- Google, Facebook spend millions on:
  - Cooling
  - Airflow
  - Power distribution
  - Measuring
  - modeling
  - Building data centers in the Arctic..

Energy

- In mobile/senor devices
  - Energy is stored in battery
  - Consumption must be low to save to battery
- Design systems/algorithms to use less energy
- Understand and model energy usage to design better systems/algorithms
  - E.g. Energy consumption in wireless communication has complex properties. Depends on distance, interference, remaining battery etc..

Communication

- Each *process* may be in a different machine, and require network to send message to others
- Processes may be on the same computer (different programs, or threads) and communicate through shared memory.
  - Faster and less costly communication

Communication

Communication model is possibly the most important step affecting distributed design

- Broadcast (all nodes hear each message)
- Point to point communication between each pair of nodes (complete graph)
- Network as a general graph
- Communication through shared memory
  - For nodes on the same machine

Communication

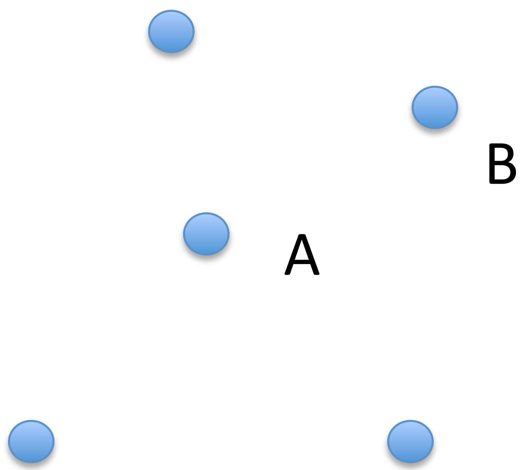
- Network as a graph can be used to represent both shared memory and message based communication
  - E.g. we can put lower weights on shared memory communication
  - What are reasonable weights?
  - Are negative weights permissible?
- Shared memory can be simulated
  - For example everyone can have a copy of the memory, that has to be updated on each event
  - Not very efficient since *n* updates must be made each time

Communication

- Broadcast not represented by a graph
- We can draw a complete graph
  - But this does not say that one transmission will reach all neighbors
- In practice, broadcast medium is still usually used for point to point communication
- So a graph is still a good representation

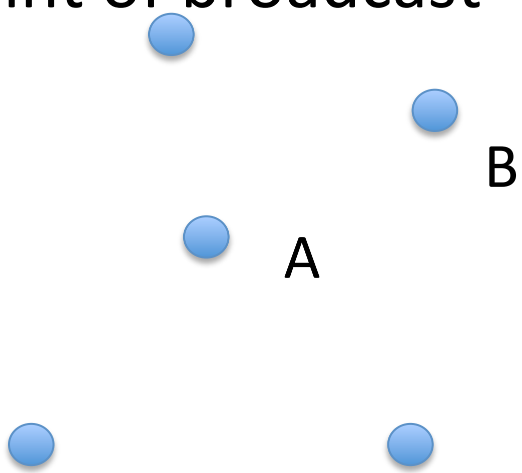
Point to point communication

- A sends a message to B
- How does A know that B received it?
- B sends an acknowledgement
- If A does not receive ack, A retransmits



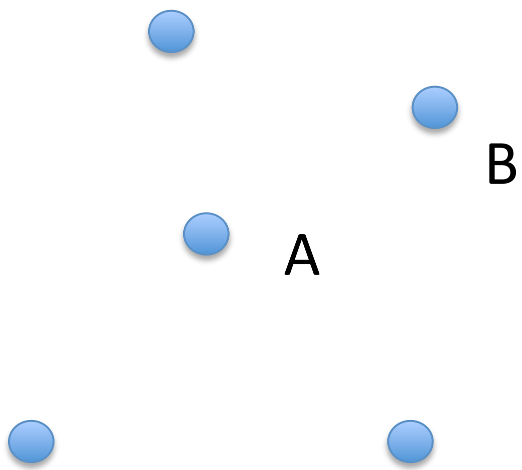
The drawback of broadcast

- A sends a message to all neighbors
- A does not know if all neighbors received it
- What if all neighbors send acks?
  - That costs n messages and time
  - Defeats the point of broadcast



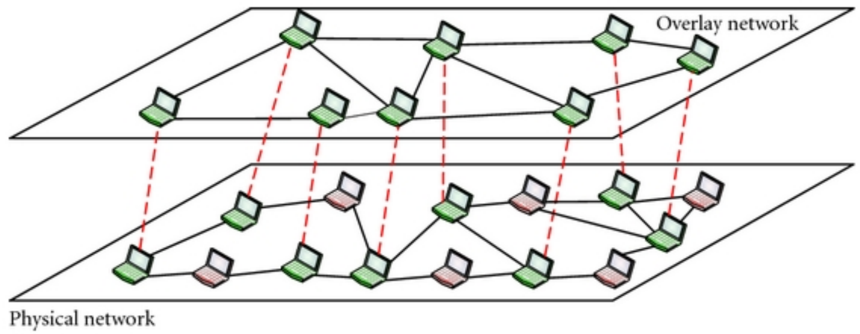
Broadcast

- Good for cases where individual messages are not critical e.g. streaming video
- Bad for important messages



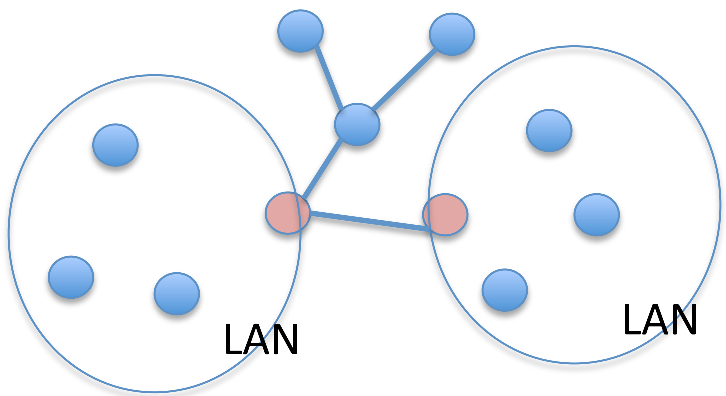
Communication: Overlay network

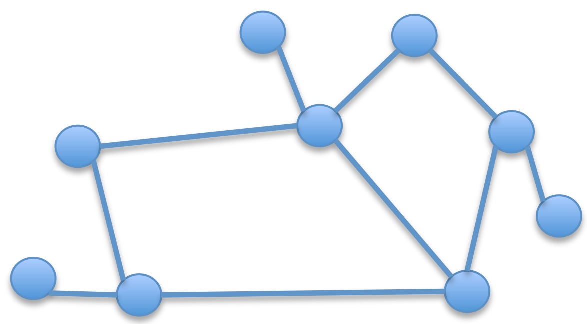
- We may sometimes ignore parts of the network
  - Nodes that carry messages but do not directly participate
  - Or edges that exist but we are not using
- Often used in peer-to-peer networks



Communication: Overlay network

- E.g. We may ignore routers, we may ignore edges that do not directly participate
- We may include edges that do not exist in reality, but are used in communication
- Depends on application
- The overlay may have no similarity to the physical network





Communication

- Remote procedure calls
  - Process A calls a function f in the code of process B
  - This is equivalent to A sending a specific type to message to B, on reading which B decides to run the function f
  - RPC is a programming abstraction that makes some types of code easier
  - Does not change our fundamental concepts of a distributed systems

Architectures

- Layered software:
  - Different layers deal with different things
  - Well defined tasks for layers, upper layer assumes lower layer is doing its job
  - E.g. network protocols

Architectures

- Client – server
  - Servers do the computation
  - Clients request computations

Architecture

- Peer to peer
  - All nodes are equivalent (equal capabilities)
  - Each can (does) as client as well as server
  - May not be clear distinction between who is requesting and who is performing tasks
  - More general than client-server

Failures

- Nodes may fail
  - Hardware failure
  - Run out of energy or power failure
  - Software failure (crash)
  - Permanent
  - Temporary (what happens when it restarts? Recovers the state? Starts from initial state?)
  - Model depends on system. E.g. different types of failures occur with corresponding probabilities

Node failures

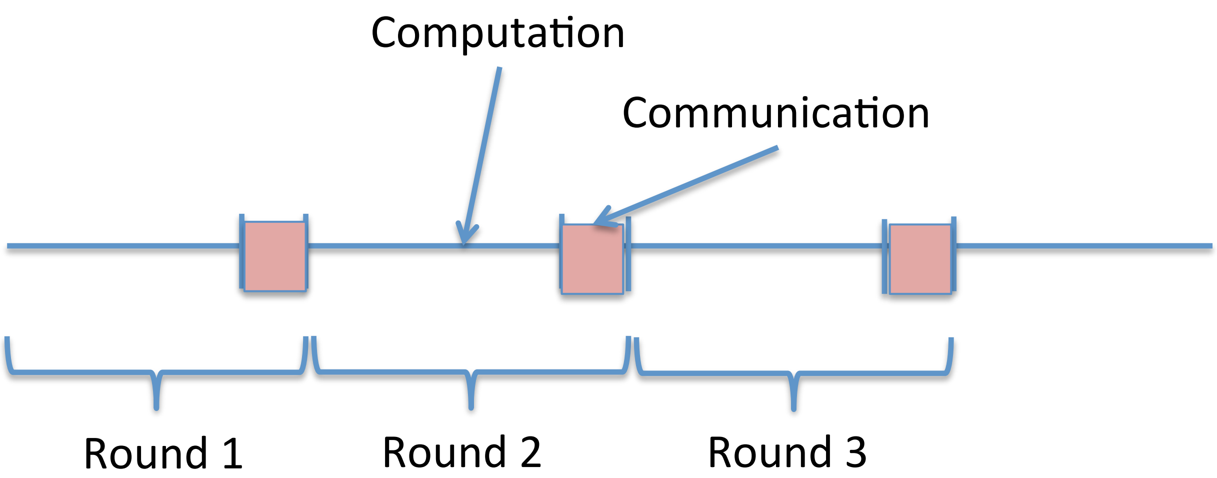
- Common abstract models
  - Stopping failure: node just stops working
    - May need assumptions about which computation/communication it finishes before stopping
    - May need assumption about neighbors knowing of failure
  - Byzantine failure: node behaves as an adversary
    - Imagine your enemy has taken control of the node
    - Is trying to spoil your computation
- Nodes may fail individually
  - E.g. each node fails with probability p
- Nodes may have correlated failure
  - E.g. all nodes fail in a region (data center, sensor field)

Link/communication failure

- May be temporary/permanent
- May happen due to
  - Hardware failure
  - Noise: electronic devices (microwaves etc) may transmit radio waves at similar frequencies and disrupt communication
  - Interference: Other communicating nodes nearby may disrupt communication
- Effects
  - Channel silent and unusable (hardware failure)
  - Channel active, but unusable due to noise and interference
  - Channel active, but may contain erroneous message (may be detected by error correcting codes)

Computation

- Synchronous:
  - Operation in rounds
  - In a round, a node performs some computation, and then sends some messages
  - All messages sent at the end of round x are available to recipients at start of round x+1
    - But not earlier



Communication

- Synchronous
  - Can be implemented if message transmission time is bounded by some constant say m
  - Computation times for all nodes are bounded by some constant c
  - Clocks are synchronized
  - Then set each round to be m+c in duration

Asynchronous Communication

- No synchronization or rounds
  - Nodes compute at different and arbitrary speeds
  - Messages proceed at different speeds: may be arbitrarily delayed, may be received at any time
- Worst case model
  - No assumption about speeds of processes or channel
  - (But does not include communication/computation errors)

Asynchronous Communication

- Harder to manage
  - Message can arrive at any time after being sent, must be handled suitably
  - Possible to make some simplifying assumptions E.g.:
    - Channels are FIFO: order of messages on a channel are preserved
    - Some code blocks are atomic (not interrupted by messages)
    - Either communication or computation times bounded

Synchronous communication in Real systems

- Synchronous communication can be a fair model
- Modern computers and networks are fast
  - (though not arbitrarily fast)
- Easier to design algorithms and analyze
- Well designed algorithms are faster and more efficient
- Often can be adapted to asynchronous systems
  - Often a starting point for design

Security

- Issues:
  - Unauthorized access, modification. Making systems unavailable (DOS)
  - Attack on one or more nodes
    - Causing to it fail
    - Read data
    - Taking control to read future data, disrupt operation
  - Attack on communication links/channel
    - Block communication
    - Read data in the channel (easy in wireless without encyption)
    - Corrupt data in the channel

Security

- Solutions usually have specific assumptions of what the adversary can do

- E.g. If adversary has access to channel
  - Cryptography may be able to prevent reading/ corrupting data

Mobility

- Movement makes it harder to design distributed systems
  - Communication is difficult
    - Delays, lost messages
    - Edge weights can change
  - Applications that depend on location must adapt to movement
- How do people move? What is a model of movement?
  - Not yet well understood

Modeling distributed systems

- Many possibilities
- Choose your assumptions carefully for your problem
- Pay close attention to what is known about communication/network
- Start with simpler models
  - Usually more assumptions, fewer parameters
  - See what can be achieved
  - Then try to drop/relax assumptions