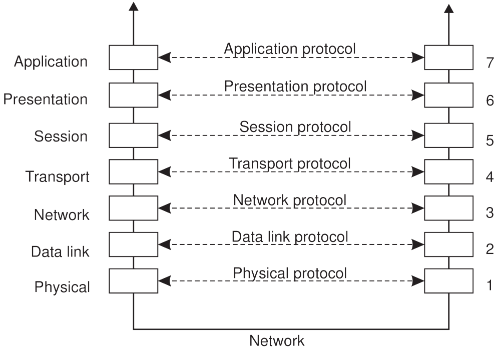
Distributed Systems

(4th edition, version 01)

Chapter 04: Communication

Basic networking model



Drawbacks

- Focus on message-passing only
- Often unneeded or unwanted functionality
- Violates access transparency

Low-level layers

Recap

- Physical layer: contains the specification and implementation of bits, and their transmission between sender and receiver
- Data link layer: prescribes the transmission of a series of bits into a frame to allow for error and flow control
- Network layer: describes how packets in a network of computers are to be routed.

Observation

For many distributed systems, the lowest-level interface is that of the network layer.

Transport Layer

Important

The transport layer provides the actual communication facilities for most distributed systems.

Standard Internet protocols

- TCP: connection-oriented, reliable, stream-oriented communication
- UDP: unreliable (best-effort) datagram communication

Middleware layer

Observation

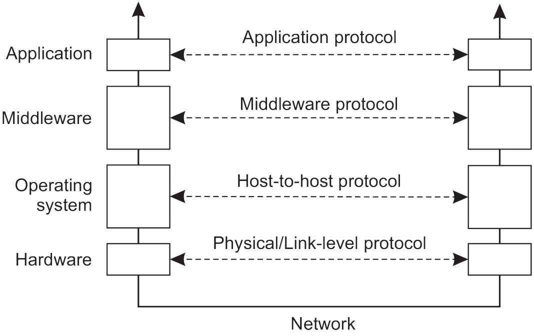
Middleware is invented to provide common services and protocols that can be used by many different applications

- A rich set of communication protocols
- (Un)marshaling of data, necessary for integrated systems
- Naming protocols, to allow easy sharing of resources
- Security protocols for secure communication
- Scaling mechanisms, such as for replication and caching

Note

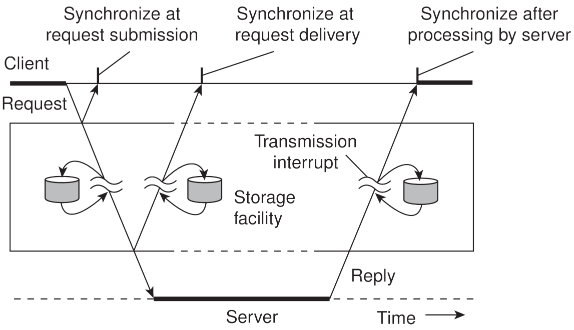
What remains are truly application-specific protocols... such as?

An adapted layering scheme



Types of communication

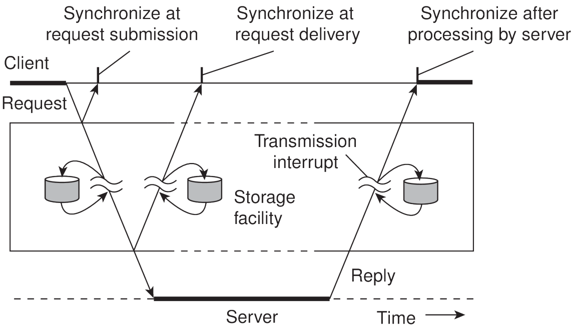
Distinguish...



- Transient versus persistent communication
- Asynchronous versus synchronous communication

Types of communication

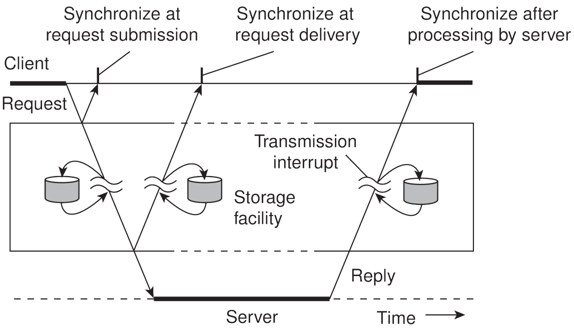
Transient versus persistent



- Transient communication: Comm. server discards message when it cannot be delivered at the next server, or at the receiver.
- Persistent communication: A message is stored at a communication server as long as it takes to deliver it.

Types of communication

Places for synchronization



- At request submission
- At request delivery
- After request processing

Client/Server

Some observations

Client/Server computing is generally based on a model of transient synchronous communication:

- Client and server have to be active at the time of communication
- Client issues request and blocks until it receives reply
- Server essentially waits only for incoming requests, and subsequently processes them

Client/Server

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Client/Server computing is generally based on a model of transient synchronous communication:

- Client and server have to be active at the time of communication
- Client issues request and blocks until it receives reply
- Server essentially waits only for incoming requests, and subsequently processes them

Drawbacks synchronous communication

- Client cannot do any other work while waiting for reply
- Failures have to be handled immediately: the client is waiting
- The model may simply not be appropriate (mail, news)

Messaging

Message-oriented middleware

Aims at high-level persistent asynchronous communication:

- Processes send each other messages, which are queued
- Sender need not wait for immediate reply, but can do other things
- Middleware often ensures fault tolerance

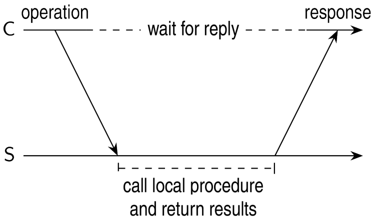
Basic RPC operation

Observations

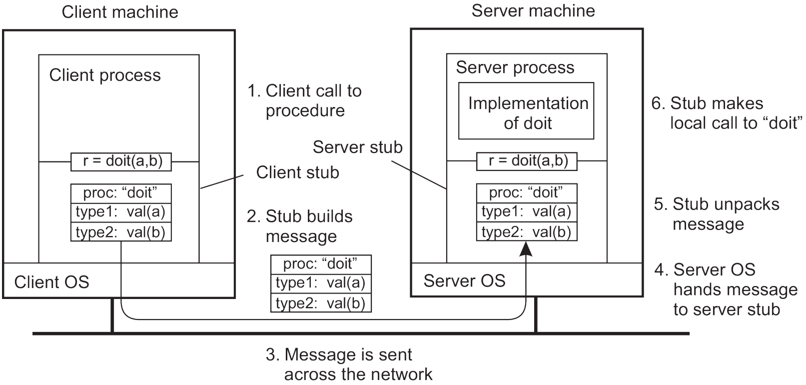
- Application developers are familiar with simple procedure model
- Well-engineered procedures operate in isolation (black box)
- There is no fundamental reason not to execute procedures on separate machine

Conclusion

Communication between caller & callee can be hidden by using procedure-call mechanism.



Basic RPC operation



1. Client procedure calls client stub.
2. Stub builds message; calls local OS.
3. OS sends message to remote OS.
4. Remote OS gives message to stub.
5. Stub unpacks parameters; calls server.
6. Server does local call; returns result to stub.
7. Stub builds message; calls OS.
8. OS sends message to client's OS.
9. Client's OS gives message to stub.
10. Client stub unpacks result; returns to client.

RPC: Parameter passing

There's more than just wrapping parameters into a message

- Client and server machines may have different data representations (think of byte ordering)
- Wrapping a parameter means transforming a value into a sequence of bytes
- Client and server have to agree on the same encoding:
  - How are basic data values represented (integers, floats, characters)
  - How are complex data values represented (arrays, unions)

Conclusion

Client and server need to properly interpret messages, transforming them into machine-dependent representations.

RPC: Parameter passing

Some assumptions

- Copy in/copy out semantics: while procedure is executed, nothing can be assumed about parameter values.
- All data that is to be operated on is passed by parameters. Excludes passing references to (global) data.

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Full access transparency cannot be realized.

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Conclusion

Full access transparency cannot be realized.

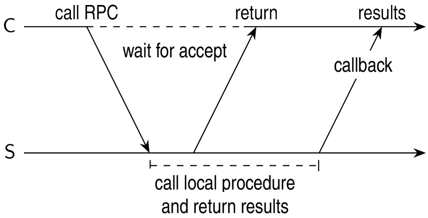
A remote reference mechanism enhances access transparency

- Remote reference offers unified access to remote data
- Remote references can be passed as parameter in RPCs
- Note: stubs can sometimes be used as such references

Asynchronous RPCs

Essence

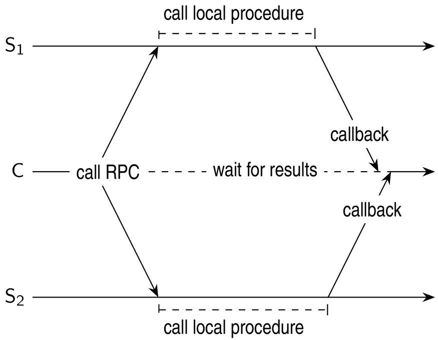
Try to get rid of the strict request-reply behavior, but let the client continue without waiting for an answer from the server.



Sending out multiple RPCs

Essence

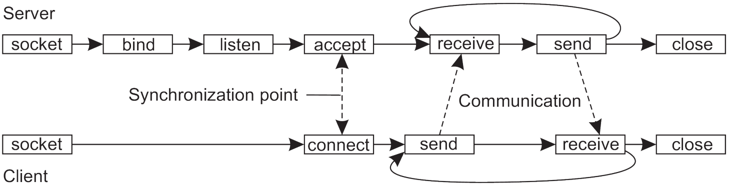
Sending an RPC request to a group of servers.



Transient messaging: sockets

Berkeley socket interface

Operation	Description
`socket`	Create a new communication end point
`bind`	Attach a local address to a socket
`listen`	Tell operating system what the maximum number of pending connection requests should be
`accept`	Block caller until a connection request arrives
`connect`	Actively attempt to establish a connection
`send`	Send some data over the connection
`receive`	Receive some data over the connection
`close`	Release the connection



Sockets: Python code

Server

```
from socket  import *

class Server:
  def run(self):
    s = socket(AF_INET, SOCK_STREAM)
    s.bind((HOST, PORT))
    s.listen(1)
    (conn, addr) = s.accept()  # returns new socket and addr. client
    while True:                # forever
      data = conn.recv(1024)   # receive data from client
      if not data: break       # stop if client stopped
      conn.send(data+b"*")     # return sent data plus an "*"
    conn.close()               # close the connection
```

Client

```
class Client:
  def run(self):
    s = socket(AF_INET, SOCK_STREAM)
    s.connect((HOST, PORT)) # connect to server (block until accepted)
    s.send(b"Hello, world") # send same data
    data = s.recv(1024)     # receive the response
    print(data)             # print what you received
    s.send(b"")             # tell the server to close
    s.close()               # close the connection
```

Making sockets easier to work with

Observation

Sockets are rather low level and programming mistakes are easily made. However, the way that they are used is often the same (such as in a client-server setting).

Alternative: ZeroMQ

Provides a higher level of expression by pairing sockets: one for sending messages at process P and a corresponding one at process Q for receiving messages. All communication is asynchronous.

Three patterns

- Request-reply
- Publish-subscribe
- Pipeline

Request-reply

```
import zmq

def server():
  context = zmq.Context()
  socket  = context.socket(zmq.REP)          # create reply socket
  socket.bind("tcp://*:12345")               # bind socket to address

  while True:
    message = socket.recv()                  # wait for incoming message
    if not "STOP" in str(message):           # if not to stop...
      reply = str(message.decode())+'*'      # append "*" to message
      socket.send(reply.encode())            # send it away (encoded)
    else:
      break                                  # break out of loop and end

def client():
  context = zmq.Context()
  socket  = context.socket(zmq.REQ)          # create request socket

  socket.connect("tcp://localhost:12345")    # block until connected
  socket.send(b"Hello world")                # send message
  message = socket.recv()                    # block until response
  socket.send(b"STOP")                       # tell server to stop
  print(message.decode())                    # print result
```

Publish-subscribe

```python
import multiprocessing
import zmq, time

def server():
  context = zmq.Context()
  socket = context.socket(zmq.PUB)           # create a publisher socket
  socket.bind("tcp://*:12345")               # bind socket to the address
  while True:
    time.sleep(5)                            # wait every 5 seconds
    t = "TIME " + time.asctime()
    socket.send(t.encode())                  # publish the current time

def client():
  context = zmq.Context()
  socket = context.socket(zmq.SUB)           # create a subscriber socket
  socket.connect("tcp://localhost:12345")    # connect to the server
  socket.setsockopt(zmq.SUBSCRIBE, b"TIME") # subscribe to TIME messages

  for i in range(5):       # Five iterations
    time = socket.recv()   # receive a message related to subscription
    print(time.decode())   # print the result
```

Pipeline

```
def producer():
  context = zmq.Context()
  socket  = context.socket(zmq.PUSH)      # create a push socket
  socket.bind("tcp://127.0.0.1:12345")    # bind socket to address

  while True:
    workload = random.randint(1, 100)     # compute workload
    socket.send(pickle.dumps(workload))   # send workload to worker
    time.sleep(workload/NWORKERS)         # balance production by waiting

def worker(id):
  context = zmq.Context()
  socket  = context.socket(zmq.PULL)      # create a pull socket
  socket.connect("tcp://localhost:12345") # connect to the producer

  while True:
    work = pickle.loads(socket.recv())     # receive work from a source
    time.sleep(work)                       # pretend to work
```

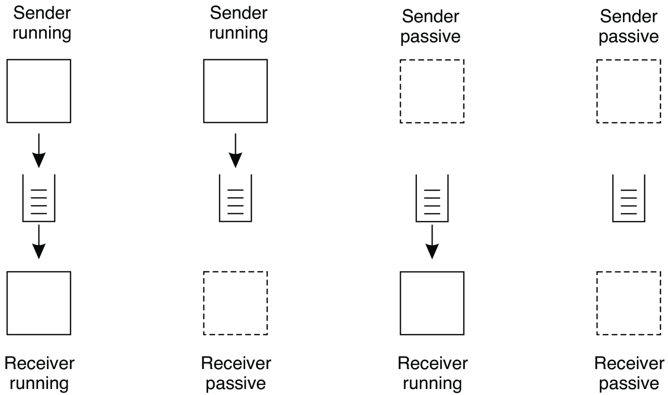
MPI: When lots of flexibility is needed

Representative operations

Operation	Description
MPI_BSEND	Append outgoing message to a local send buffer
MPI_SEND	Send a message and wait until copied to local or remote buffer
MPI_SSEND	Send a message and wait until transmission starts
MPI_SENDRECV	Send a message and wait for reply
MPI_ISEND	Pass reference to outgoing message, and continue
MPI_ISSEND	Pass reference to outgoing message, and wait until receipt starts
MPI_RECV	Receive a message; block if there is none
MPI_IRECV	Check if there is an incoming message, but do not block

Queue-based messaging

Four possible combinations



Message-oriented middleware

Essence

Asynchronous persistent communication through support of middleware-level queues. Queues correspond to buffers at communication servers.

Operations

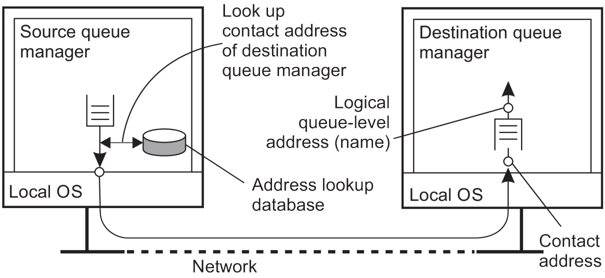
Operation	Description
PUT	Append a message to a specified queue
GET	Block until the specified queue is nonempty, and remove the first message
POLL	Check a specified queue for messages, and remove the first. Never block
NOTIFY	Install a handler to be called when a message is put into the specified queue

General model

Queue managers

Queues are managed by queue managers. An application can put messages only into a local queue. Getting a message is possible by extracting it from a local queue only ⇒ queue managers need to route messages.

Routing



Message broker

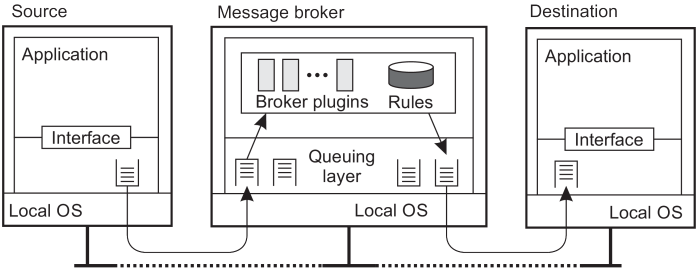
Observation

Message queuing systems assume a common messaging protocol: all applications agree on message format (i.e., structure and data representation)

Broker handles application heterogeneity in an MQ system

- Transforms incoming messages to target format
- Very often acts as an application gateway
- May provide subject-based routing capabilities (i.e., publish-subscribe capabilities)

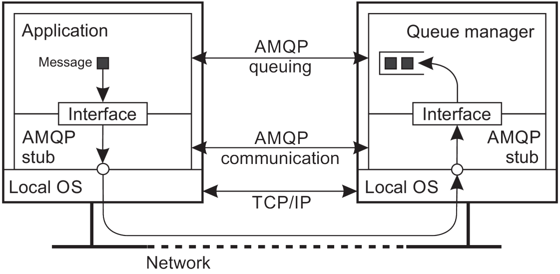
Message broker: general architecture



Example: AMQP

Lack of standardization

Advanced Message-Queuing Protocol was intended to play the same role as, for example, TCP in networks: a protocol for high-level messaging with different implementations.



Basic model

Client sets up a (stable) connection, which is a container for serveral (possibly ephemeral) one-way channels. Two one-way channels can form a session. A link is akin to a socket, and maintains state about message transfers.

Example: AMQP-based producer

```python
import rabbitpy

def producer():
  connection = rabbitpy.Connection() # Connect to RabbitMQ server
  channel = connection.channel()     # Create new channel on the connection

  exchange = rabbitpy.Exchange(channel, 'exchange') # Create an exchange
  exchange.declare()

  queue1 = rabbitpy.Queue(channel, 'example1') # Create 1st queue
  queue1.declare()

  queue2 = rabbitpy.Queue(channel, 'example2') # Create 2nd queue
  queue2.declare()

  queue1.bind(exchange, 'example-key') # Bind queue1 to a single key
  queue2.bind(exchange, 'example-key') # Bind queue2 to the same key

  message = rabbitpy.Message(channel, 'Test message')
  message.publish(exchange, 'example-key') # Publish the message using the key
  exchange.delete()
```

Example: AMQP-based consumer

```
import rabbitpy

def consumer():
  connection = rabbitpy.Connection()
  channel = connection.channel()

  queue = rabbitpy.Queue(channel, 'example1')

  # While there are messages in the queue, fetch them using Basic.Get
  while len(queue) > 0:
    message = queue.get()
    print('Message Q1: %s' % message.body.decode())
    message.ack()

  queue = rabbitpy.Queue(channel, 'example2')

  while len(queue) > 0:
    message = queue.get()
    print('Message Q2: %s' % message.body.decode())
    message.ack()
```

Application-level multicasting

Essence

Organize nodes of a distributed system into an overlay network and use that network to disseminate data:

- Oftentimes a tree, leading to unique paths
- Alternatively, also mesh networks, requiring a form of routing

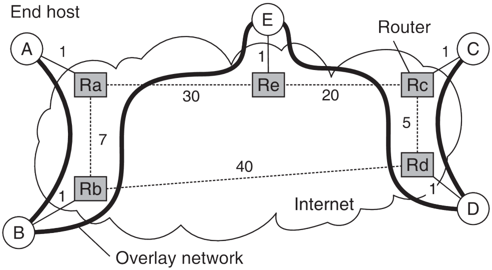
Application-level multicasting in Chord

Basic approach

1. Initiator generates a multicast identifier *mid*.
2. Lookup *succ*(*mid*), the node responsible for *mid*.
3. Request is routed to *succ*(*mid*), which will become the root.
4. If *P* wants to join, it sends a join request to the root.
5. When request arrives at *Q*:
    - *Q* has not seen a join request before ⇒ it becomes forwarder; *P* becomes child of *Q*. Join request continues to be forwarded.
    - *Q* knows about tree ⇒ *P* becomes child of *Q*. No need to forward join request anymore.

ALM: Some costs

Different metrics

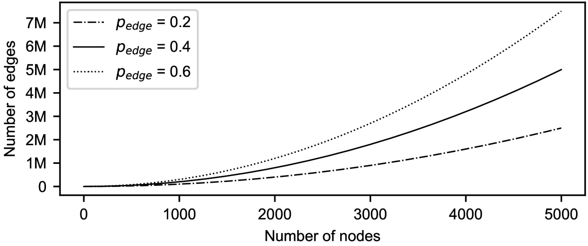


- Link stress: How often does an ALM message cross the same physical link? Example: message from A to D needs to cross $\langle Ra, Rb \rangle$ twice.
- Stretch: Ratio in delay between ALM-level path and network-level path. Example: messages B to C follow path of length 73 at ALM, but 47 at network level $\Rightarrow$ stretch = 73/47.

Flooding

Essence

P simply sends a message m to each of its neighbors. Each neighbor will forward that message, except to P, and only if it had not seen m before.



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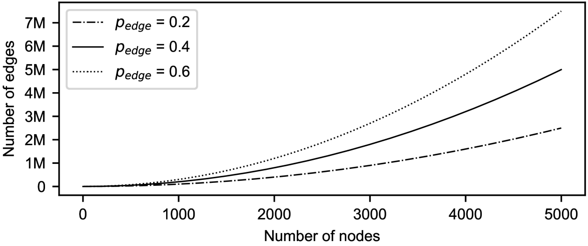


Variation

Let Q forward a message with a certain probability p_{flood}, possibly even dependent on its own number of neighbors (i.e., node degree) or the degree of its neighbors.

Epidemic protocols

Assume there are no write–write conflicts

- Update operations are performed at a single server
- A replica passes updated state to only a few neighbors
- Update propagation is lazy, i.e., not immediate
- Eventually, each update should reach every replica

Two forms of epidemics

- Anti-entropy: Each replica regularly chooses another replica at random, and exchanges state differences, leading to identical states at both afterwards
- Rumor spreading: A replica which has just been updated (i.e., has been contaminated), tells several other replicas about its update (contaminating them as well).

Anti-entropy

Principle operations

- A node P selects another node Q from the system at random.
- Pull: P only pulls in new updates from Q
- Push: P only pushes its own updates to Q
- Push-pull: P and Q send updates to each other

Observation

For push-pull it takes $\mathcal{O}(log(N))$ rounds to disseminate updates to all N nodes (round = when every node has taken the initiative to start an exchange).

Anti-entropy: analysis

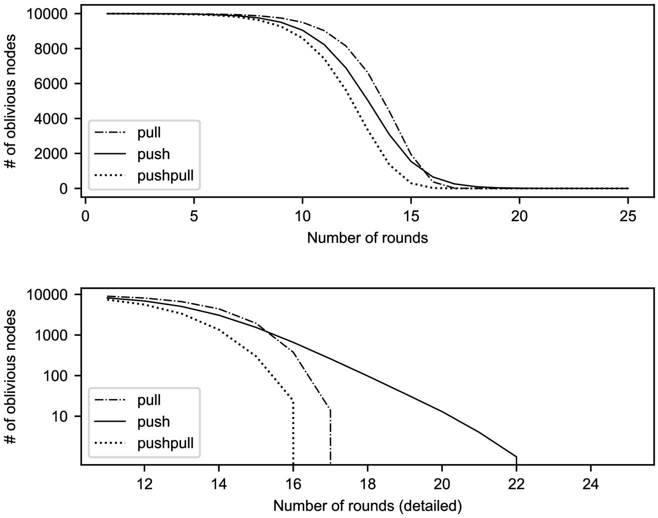
Basics

Consider a single source, propagating its update. Let p_i be the probability that a node has not received the update after the i^{th} round.

Analysis: staying ignorant

- With pull, $p_{i+1} = (p_i)^2$: the node was not updated during the i^{th} round and should contact another ignorant node during the next round.
- With push, $p_{i+1} = p_i(1 - \frac{1}{N-1})^{(N-1)(1-p_i)} \approx p_i e^{-1}$ (for small p_i and large N): the node was ignorant during the i^{th} round and no updated node chooses to contact it during the next round.
- With push-pull: $(p_i)^2 \cdot (p_i e^{-1})$

Anti-entropy performance



Rumor spreading

Basic model

A server S having an update to report, contacts other servers. If a server is contacted to which the update has already propagated, S stops contacting other servers with probability p_{stop}.

Observation

If s is the fraction of ignorant servers (i.e., which are unaware of the update), it can be shown that with many servers

$$s = e^{-(1/p_{stop}+1)(1-s)}$$

Formal analysis

Notations

Let s denote fraction of nodes that have not yet been updated (i.e., susceptible; i the fraction of updated (infected) and active nodes; and r the fraction of updated nodes that gave up (removed).

From theory of epidemics

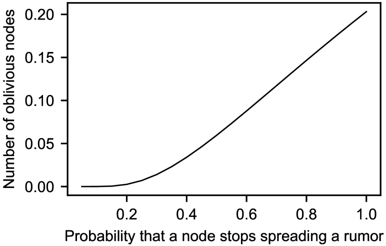
$$
\begin{array}{llcl}
(1) & ds/dt & = & -s \cdot i \\
(2) & di/dt & = & s \cdot i - p_{stop} \cdot (1-s) \cdot i \\
\Rightarrow & di/ds & = & -(1+p_{stop}) + \frac{p_{stop}}{s} \\
\Rightarrow & i(s) & = & -(1+p_{stop}) \cdot s + p_{stop} \cdot \ln(s) + C
\end{array}
$$

Wrap up

$i(1) = 0 \Rightarrow C = 1 + p_{stop} \Rightarrow i(s) = (1+p_{stop}) \cdot (1-s) + p_{stop} \cdot \ln(s)$. We are looking for the case $i(s) = 0$, which leads to $s = e^{-(1/p_{stop}+1)(1-s)}$

Rumor spreading

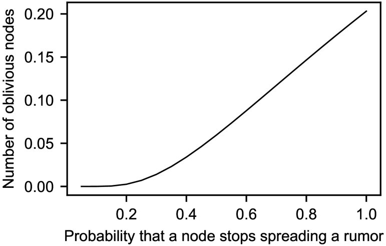
The effect of stopping



Consider 10,000 nodes		
$1/p_{stop}$	s	N_s
1	0.203188	2032
2	0.059520	595
3	0.019827	198
4	0.006977	70
5	0.002516	25
6	0.000918	9
7	0.000336	3

Rumor spreading

The effect of stopping



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7	0.000336	3

Note

If we really have to ensure that all servers are eventually updated, rumor spreading alone is not enough

Deleting values

Fundamental problem

We cannot remove an old value from a server and expect the removal to propagate. Instead, mere removal will be undone in due time using epidemic algorithms

Solution

Removal has to be registered as a special update by inserting a death certificate

Deleting values

When to remove a death certificate (it is not allowed to stay for ever)

- Run a global algorithm to detect whether the removal is known everywhere, and then collect the death certificates (looks like garbage collection)
- Assume death certificates propagate in finite time, and associate a maximum lifetime for a certificate (can be done at risk of not reaching all servers)

Note

It is necessary that a removal actually reaches all servers.