Scalability

Protocol Design – S-38.3157

A typical design argument:

"This does not scale…"

- Why?
- With respect to what?
- Does it have to?

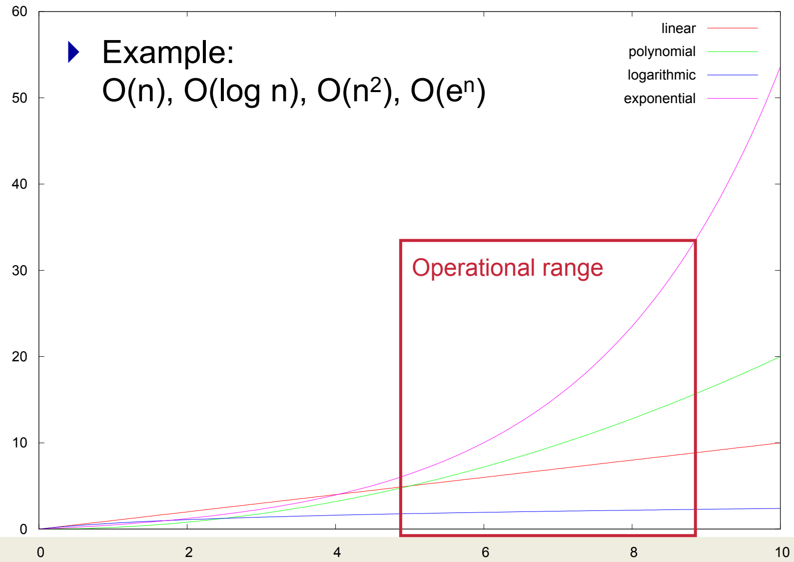
Scalability in General

Common use (not just) in communications

- Capability of a system to operate across a range of settings
  - As opposed to being constrained to a single operational point
- Measuring change / evolution of a system property
- Depending on a (set of) certain input parameter(s)
  - Applicability defined by the range of acceptable input parameters (for the which the resulting system properties are workable)
- Closely coupled to resource consumption (and thus fairness)
- Relation to complexity theory
  - Classification of resource consumption of algorithms depending on the input
    Complexity classes (order of): $O(1)$, $O(n)$, $O(\log n)$, $O(n^k)$, $O(e^n)$

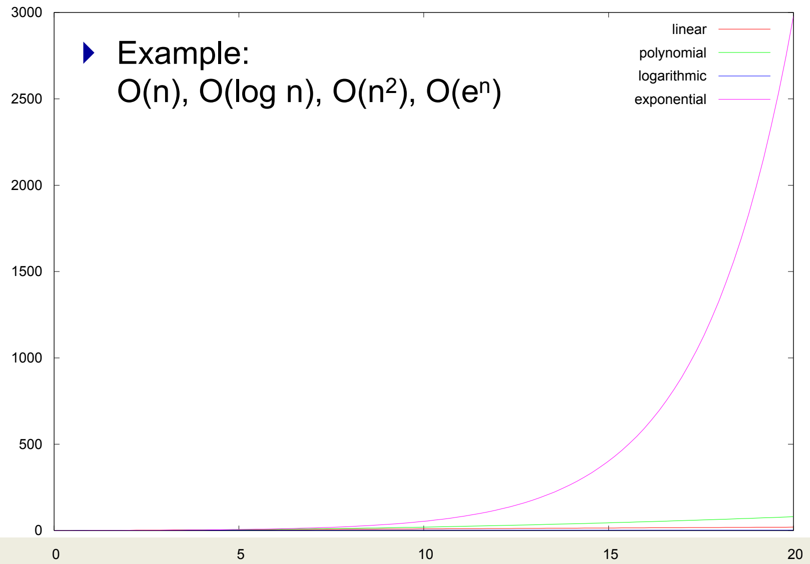
Scale as a Measure (1)

- Example:
  $O(n)$, $O(\log n)$, $O(n^2)$, $O(e^n)$



Scale as a Measure (2)

- Example:
  O(n), O(log n), O(n^2), O(e^n)

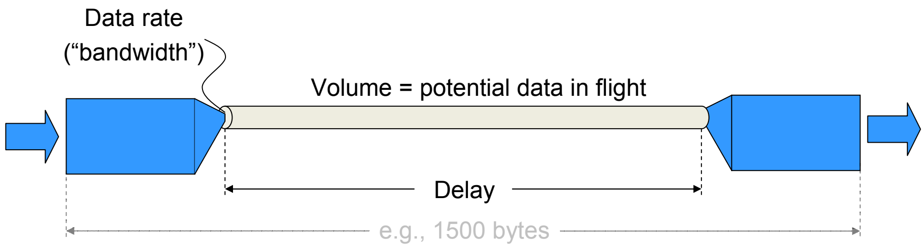


Areas of Scalability: Network Side

- Path length (number of hops, delay, delay variation)
  - Distance-dependent delay due to speed of light + processing/queuing delay per hop
  - Local link or same host vs. some 30 hops to Australia
  - < 1ms on a local link vs. several seconds via GPRS or satellite
    - vs. minutes or hours or days when talking to a spacecraft (or other remote peers)
  - Close to constant delay on a local link vs. several seconds jitter via satellite
    - Incurred by medium access protocol
- Loss rate
  - Virtually no loss on a local wired link vs. <10% loss for Internet traffic
  - Unpredictable loss rate and pattern for wireless networks
  - Individual losses (following some distribution) vs. bursty losses
- Data rate
  - Some 100 bit/s acoustic underwater modem vs. Tbit/s fiber optic link
- Degree of multiplexing
  - How much influence does the own traffic have on the network?
  - Access link vs. backbone link

Areas of Scalability: Network Side (2)

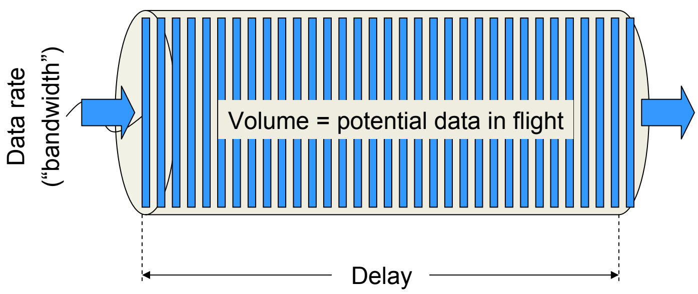
- Particular issue: long fat pipes (“bandwidth x delay” product)
  - Enabling efficient and quick full utilization without knowing pipe characteristics and third party traffic
  - No problem in traditional wired networks
  - Example: ISDN link @ 64 kbit/s x 10ms delay = ~800 Bytes



Only one packet in transit: first bits of packet are received before last bits have been sent

Areas of Scalability: Network Side (3)

- Long fat pipes (High “bandwidth x delay” product)
  - Many packets can be “in flight”



Examples: DVB-S2 geostationary satellite @ 90 Mbit/s x 250ms delay = ~2.8 MB
Fiber optic transatlantic link @ 10 Gbit/s x 25ms delay = ~31 MB

Areas of Scalability: Application Side

- Update or request rate
  - Measured in operations per second vs. per hour vs. per day vs. per year
  - Convergence time vs. period between two updates
- Item size
  - Data fitting into a single MTU or not
  - File size from some 10 bytes to 10 GB (and beyond)
    - Impact of per operation overhead
- Number of entities (users, networks, systems)
  - How many are active (sending operations)
  - How must agree on common state as a result of the protocol operation
  - Dynamics: How does this number vary?
- Number spaces
  - In the protocol (see above) and in the operating system
  - Example: C10K problem: handling 10,000(s) clients with a server
    - Requires enough port numbers for demuxing, local identifiers (e.g., file descriptors), …

Scalability Dynamics

- Network characteristics may vary heavily and frequently
  - Depending on a protocol entity's own activity
  - Depending on traffic generated by others
  - Depending on network routing changes (e.g., in response to failure)
- Application characteristics may vary
  - Size of data items (e.g., file size)
  - Number of involved systems interacting with one another (for group communications)
  - Number of involved systems operating in parallel (parallel clients for a server)
- Variations are usually not predictable
  - Example: Flash crowds

Meta Aspect: Complexity

- Protocol Complexity
  - MUST/SHOULD/MAY in the protocol spec, number of options
    - "Hard + easy = harder than hard"
  - State machine complexity
    - E.g., number of state and state transitions, synchronization requirements
    - # transitions (and interactions) to achieve a result, interdependence of entities
  - Operation complexity
    - E.g., parsing protocol messages
  - Computational complexity
    - E.g., crypto, routing, and lookup algorithms
- Issue of backwards compatibility
  - Deployment considerations usually require dealing with older versions
  - Limits the freedom to introduce new functionality and better mechanisms
  - May lead to additional complexity if special treatment of "legacy nodes" is needed
  - ➔ Evolvability

Example: IGMPv2 (1)

Plain IGMPv2 state diagram for hosts (almost complete)

```
                             ________________
                            |                |
                            |                |
                            |                |
                            |                |
                  --------->|   Non-Member   |<---------
                 |          |                |          |
                 |          |                |          |
                 |          |                |          |
                 |          |________________|          |
                 |                   |                  |
                 | leave group       | join group       | leave group
                 | (stop timer,      |(send report,     | (send leave
                 |  send leave if    | set flag,        |  if flag set)
                 |  flag set)        | start timer)     |
         ________|________           |          ________|________
        |                 |<---------          |                 |
        |                 |                    |                 |
        |                 |<-------------------|                 |
        |                 |   query received   |                 |
        | Delaying Member |    (start timer)   |   Idle Member   |
   ---->|                 |------------------->|                 |
  |     |                 |   report received  |                 |
  |     |                 |    (stop timer,    |                 |
  |     |                 |     clear flag)    |                 |
  |     |_________________|------------------->|_________________|
  | query received    |        timer expired
  | (reset timer if   |        (send report,
  |  Max Resp Time    |         set flag)
  |  < current timer) |
   -------------------
```

Example: IGMPv2 (2)

IGMPv2 state diagram considering backward compatibility with IGMPv1 nodes

```
                             ________________
 ----------------------------|                |<------------------------
|                            |                |timer expired           |
|               timer expired|   No Members   |(notify routing -,      |
|          (notify routing -)|    Present     |clear rxmt tmr)         |
|                    ------->|                |<-------                |
|                   |        |                |       |                |
|v1 report rec'd    |        |                |       | ------------   |
|(notify routing +, |        |________________|       | | rexmt timer| |
| start timer,      |                    |            | |  expired   | |
| start v1 host     |  v2 report received|            | | (send g-s  | |
|  timer)           |  (notify routing +,|            | |  query,    | |
|                   |        start timer)|            | |  st rxmt   | |
|        ___________|______              |      ______|_|______ tmr) | |
|       |                  |<------------       |              |     | |
|       |                  |                    |              |<----- |
|       |                  | v2 report received |              |       |
|       |                  | (start timer)      |              |       |
|       | Members Present  |<-------------------|   Checking   |       |
|  ---->|                  | leave received     |  Membership  |       |
| |     |                  | (start timer*,     |              |       |
| |     |                  |  start rexmt timer,|              |       |
| |     |                  |  send g-s query)   |              |       |
| |  -->|                  |------------------->|              |       |
| | |   |__________________|                    |______________|       |
| | |v2 report rec'd |  |                          |                   |
| | |(start timer)   |  |v1 report rec'd           |v1 report rec'd    |
| |  ----------------   |(start timer,             |(start timer,      |
| |v1 host              | start v1 host timer)     | start v1 host     |
| |tmr    ______________V__                        | timer)            |
| |exp'd |                 |<-----------------------                   |
|  ------|                 |                                           |
|        |    Version 1    |timer expired                              |
|        | Members Present |(notify routing -)                         |
 ------->|                 |-------------------------------------------
         |                 |<--------------------
 ------->|_________________| v1 report rec'd     |
| v2 report rec'd |   |   (start timer,          |
| (start timer)   |   |    start v1 host timer)  |
 -----------------     -------------------------
```

Note:
Functionality ("fast leave") gets lost with presence of just one v1 host

Meta Aspect: Complexity (2)

- Implementation complexity
  - CPU requirements (related to operation and computational complexity)
  - Memory requirements (code, data – related to state machine complexity)
  - Disk space requirements
  - Other resources…
- Platform scale
  - Battery operated lightswitch
  - Tiny embedded systems (TCP stack in 4 KB)
  - Price-sensitive consumer widget/TV/car
  - Phone or PDA
  - Powerful desktop or laptop PC
  - High-end multi-CPU machines, server farm

Implementation Scalability

- C10K Problem: Examples
  - Frequency of interactions
    - Particularly expensive operations such as accepting and closing connections, security, …
  - Multiplexing and I/O handling
    - Processes vs. threads vs. single-threaded handling
    - Issues with system call efficiency (e.g., poll (), select ())
      - Solutions: kqueue (BSD) / epoll (Linux)
    - Processing many events simply takes time
  - Data access
    - Seek operations on a hard drive when retrieving file blocks for many clients
      - Hard drives are "fast" unless multiplexed
      - Example: video-on-demand streaming
    - System bus bandwidth
    - I/O subsystem performance
      - Example: file transfer from/to a Windows machine (using cygwin)
      - Limited to 2–3 MB/s on 1.7 GHz laptop running MS Windows XP
  - Interaction with other processes on the same machine

Implementation Scalability (2)

- Load balancing
  - Use of server farms for load sharing
  - Load distribution e.g. by means of DNS, proxies
  - Possibly decentralized to improve access locality
    - And thus also avoid the impact of long paths
  - Issue: need for synchronizing servers in a farm?

Operational Complexity

- Networks and systems need to be run
- How many parameters need to be configured?
  - How do they interact?
  - How much coordination (e.g., across different organizations) is needed?
  - (How) can misconfigurations be detected?
  - Manual vs. automated process
- Monitoring, diagnostics
  - Which parameters? Where? Frequency? …?
- Failures
  - Graceful degradation vs. complete breakdown
  - How to track and debug failures?
  - How much action is needed for recovery?
  - How long does this take?

Meta Aspect: Economics

- Cost may be associated with data transmission
  - Rate, volume, packets, QoS, …
- Cost is directly associated with implementation complexity
  - Manpower for system design, implementation, and testing
  - Devices requirements
- Benefit is indirectly associated with protocol complexity
  - Successful deployments require working and interoperable products
  - Metcalfe's law
  - Complexity creates adoption hurdles
- Financial scaling
- (cf. Social scaling)

Limiting Scalability

- Scalability is usually another design tradeoff, per parameter
  - Scalability vs. protocol and implementation complexity, resource utilization, …
  - Quick results vs. longer term perspectives
- Limiting applicability may be dangerous
  - Protocols may often be used outside their intended areas of application
  - Exceptions: e.g., intra-system communications in contained environments
- Dealing with scaling beyond expectation
  - Graceful degradation (of quality or functionality)
  - Clean failure
  - Make sure the protocol does not run havoc / create damage

Scalability Mechanisms by Example

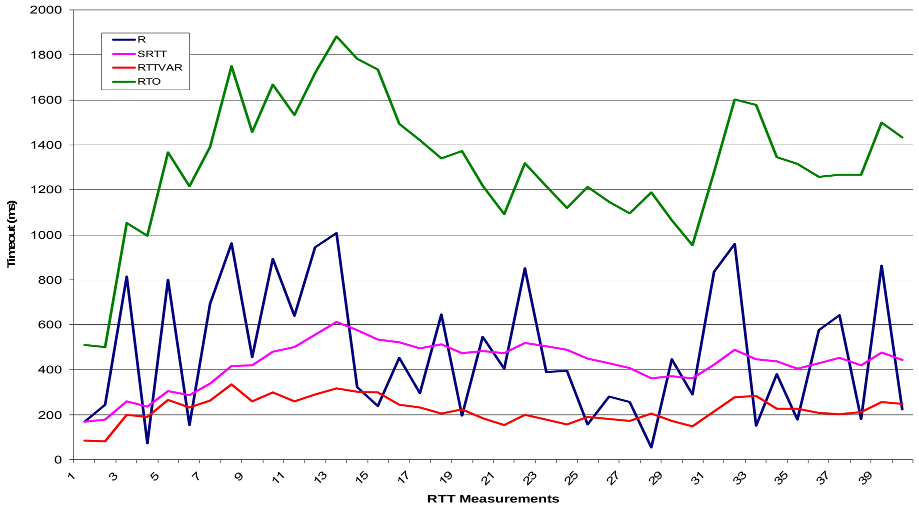
Mechanisms: Timeouts

- Path length
  - Primary impact on delay and delay variation
  - Packet loss and degree of multiplexing covered below
- Issue: Protocols require timers and timeouts
  - Any statically selected value is likely to wrong in some environment
    - Limiting factor for efficiency: too large ones may keep the network idle
    - Cause of unnecessary overhead: too small ones may lead to early retransmissions
  - Example: NFS used 500 ms
- Solution: Adaptive timers
  - Measure observed RTT and adjust timers accordingly
  - Use moving averages to avoid oscillation to short-term changes
  - Take a sufficiently conservative initial values that will not cause harm

Example: TCP RTO Calculation

- TCP Retransmission Timeout (RTO)
  - Used to determine that a packet got lost and needs retransmission
  - Typically an indication of network congestion
    - Side effect: return to slow start operation
  - Underestimating worse than overestimating
    - Premature RTO will harm performance seriously (spurious retransmits, slow start!)
    - Late RTO will delay repair and hence also harm performance
- Algorithm
  - RTTVAR (RTT variation) and SRTT (smoothed RTT); G: clock granularity
    - Initial RTO = 3s
  - Upon first RTT measurement (R)
    - SRTT = R   RTTVAR = R/2
    - RTO = SRTT + max (G, K x RTTVAR)   [K=4]
  - For each subsequent RTT measurement (R')
    - RTTVAR = (1 – β) x RTTVAR + β x | SRTT – R' | [β = 1/4]
    - SRTT = (1 – α) x SRTT + α x R'   [α = 1/8]
    - RTO = SRTT + max (G, K x RTTVAR)   [K=4]

TCP RTO Example



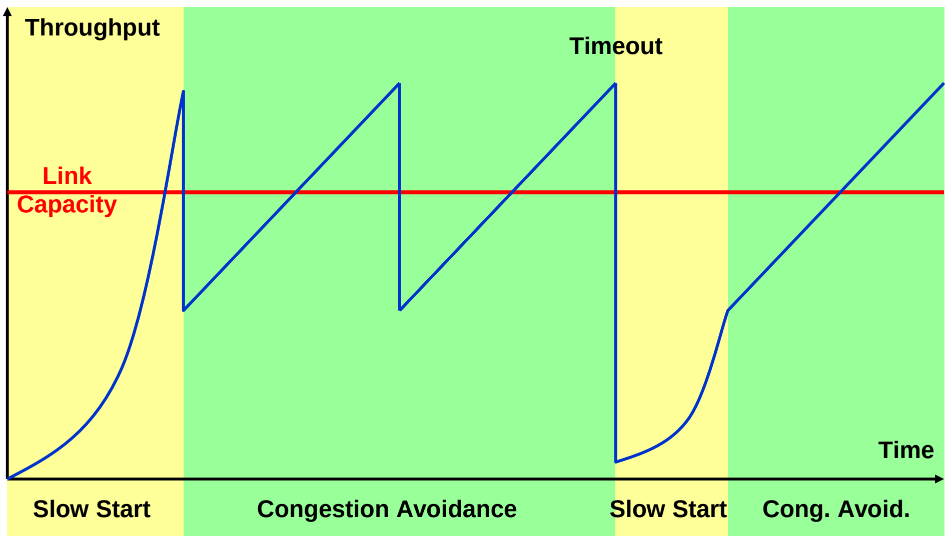
Packet loss rate

- Loss rate
  - Example: Go-Back-N vs. SACK
  - Partially dependent on the degree of multiplexing
- Issue: distinguishing congestion losses and corruption losses
  - E.g., observing RTO as one hint for congestion likelihood
- General: congestion control
  - Reduction of data rate
  - Reduction of packet frequency
- Losses due to bit errors
  - Forward error correction (bit or packet-based)
  - Adaptive retransmission schemes

Mechanisms: Congestion Control

- Data rate
  - Obviously bounded by the slowest link in the path (upper bound)
  - Dependent on the current network load (and thus variable)
  - Other factors: delay and packet losses
- Issue: fair resource sharing vs. maximizing resource utilization
  - Protocol entities operate in unknown and changing environments
  - Again, no initial value for a data rate can be assumed
    - Pessimistic assumptions (low rate) may result in underutilization
    - Optimistic assumptions (high rate) may result in overload and lead to congestion
- Solution: dynamic adaptation of data rate
  - Many different options for rate adaptation
    - Not too conservative (to avoid wasting resources)
    - Not too aggressive (to avoid congestion)

Example: Simplified TCP Operation



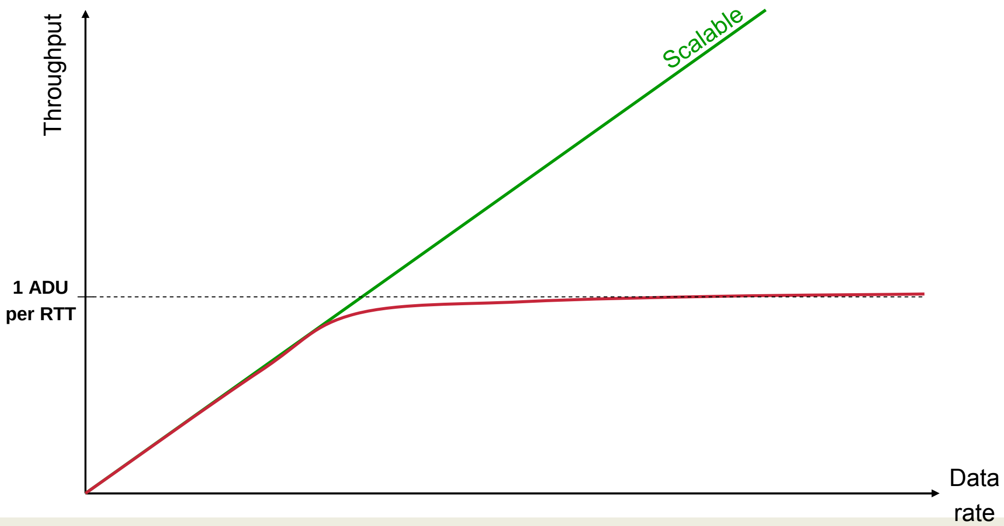
Dealing with Long Fat Pipes

- Networks with large delay x bandwidth product
  - Sufficient bandwidth available
  - Yet limited communication performance
- Issue: peers cannot utilize available capacity
  - Limitations due to protocol parameters
    - Example: TCP Window size limited the amount of data in flight to 64 KB
  - Limitations due to protocol interactions
    - Examples: Lock-step operation of SMTP initial handshake, of HTTP when downloading web pages, of POP3 when downloading emails, of SMB when accessing files
- Some solutions
  - Sufficiently dimensioned parameters (expect the unexpected)
    - TCP: Window scaling option to multiply advertised window size by 2^x
  - Minimize the number of end-to-end interactions
    - SMTP, HTTP: pipelining of requests to avoid RTT penalty

Real-world Examples: X11 and SMB in LFNs

- X11 Protocol
  - Designed for LANs
  - Frequent request-response interaction between client and server
    - Often lock step operation required: operation n+1 depends on result of operation n
  - Many small successive operations cause poor performance
    - Link capacity is not the bottleneck
- Server Message Block (SMB)
  - Resource (e.g., file and printer) access in LANs
  - RPC-style abstraction leads to horrible implementations
    - Synchronous function calls, apparently assumed to complete in virtually no time
    - Repeated invocation of the same methods
  - Extremely poor performance over long delay links (e.g., satellites)
    - Example: complete file transfer (~15 MB) takes 2.5s in LAN @ RTT=1ms but requires ~6 minutes @ RTT=1s
- General solution: Performance Enhancing Proxies (PEPs) for applications

Lock-step Protocols hit an RTT Ceiling



Impact of Data Rate

- Complexity of protocol and algorithmic operations may be limited by data rate
  - Different scaling of data rate and processing power
  - Processing is one potential bottleneck
- Examples
  - Plain packet forwarding vs. policy-based routing
    - The former works across all wire speeds
    - The latter is limited to “slower” links (no per packet route calculation possible)
  - Tradeoff across different crypto algorithms
    - Public key cryptography operations expensive to compute: limited to small amounts of data and occasional use
    - Symmetric crypto algorithms suitable for higher data rates

Scaling to large Numbers (1)

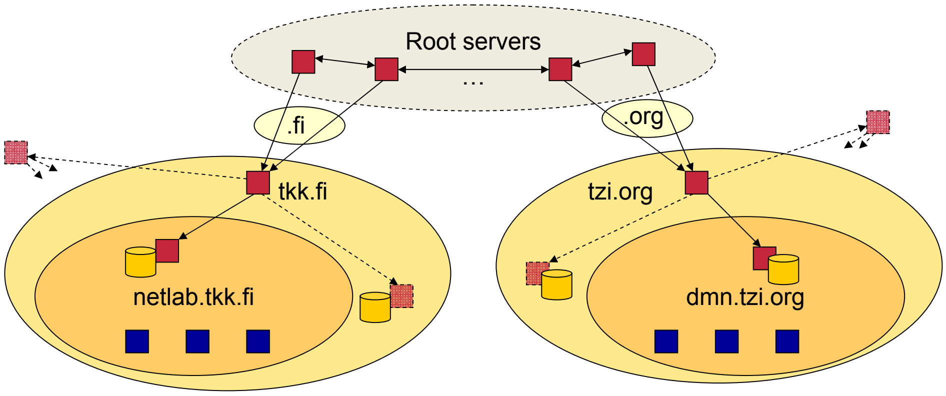
- …of items, users, systems
- Decentralized operation
  - Also helps with load sharing for implementations
- Passive: Caching
  - Web caches, DNS
- Active: Content replication
  - Streaming servers for media on demand content
  - Web servers for news agencies
- Tradeoff: keeping content current (and synchronized)
  - How well can applications deal with (slightly) out-of-date data?
  - Update frequency from server side only (web and streaming servers)
  - May incur significant complexity with update operations from client (e.g., distributed databases)

Example: DNS

- Key features
  - Distributed model: cooperation between servers
  - Redundant servers: avoid single point of failure in zone
    - one primary and one or more secondary servers
- Hierarchical structure of domain names
  - For decentralized administration and operation
  - Straightforward delegation of responsibility
- General purpose: not restricted to IP addresses
  - Could map anything
  - Stores additional information about domains
- Scalability mechanisms
  - Bottom-up search: exploit locality of requests
  - Efficiency through caching
  - Active replication of partial information (DNS servers for domains vs. contents)

Example: DNS (2)

- Decentralization, delegation, locality



- Dynamic Delegation Discovery System (DDDS)

Limits to Caching

- Diversity of item access must be limited relative to cache size
  - Working set must fit
  - Locality helps
- Sufficient number of requests relative to lifetime of cached items
- Example: Route caching
  - Works for AS router with small number of entries in forwarding information base
  - Does not work for backbone router with large FIB

Scaling to Large Numbers (2): Deferring Operations

- Late binding
  - Resolve bindings (e.g. name to address mapping) as late as possible
  - Allows operation with partial knowledge – no global synchronization needed
  - Example: IP telephony
    - SIP User Agents may defer address resolution to their local server
      - Saves complexity in the endpoint
      - Saves communication overhead (as the server may perform efficient caching)
    - User location is only performed at the called user’s server
  - Counter-example: DNS
    - IP address needed for any communication
    - Name to address resolution carried out by the endpoint
      - Requires globally connected naming infrastructure
      - Exception (counter-counter-example): HTTP proxies resolve names for their clients
- Lazy Evaluation
  - Do not calculate a result before it is known to be really needed

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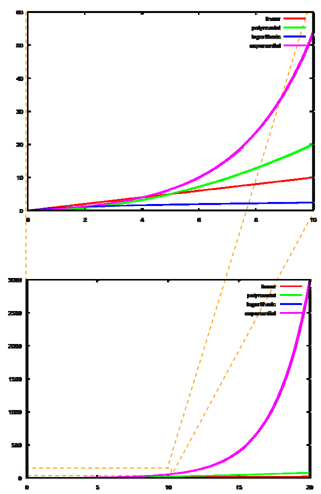
Tuesday Summary

- Scalability: constant, logarithmic, linear, polynomial, exponential relationships
- Relative to multiple parameters: (sizes, rates, numbers, …)
- “Protocol designer’s toolkit”
  - Adaptiveness (measure and react)
  - Decentralization, caching, …
- Scalability also is about economics
  - Throw more hardware vs. better design



Scaling to Large Numbers (3): Hierarchies

- "Divide and conquer"
  - Subdivide the large problem into more manageable pieces
- Example: Directory services
  - E.g., DNS hierarchy
- Example: Routing protocols
  - Autonomous systems
  - Distinction between Inter-domain and intra-domain routing
    - Only network prefixes are known outside a domain, internal structure is "hidden"
    - Network prefixes may be further aggregated
  - CIDR: Classless inter-domain routing
    - Aggregation of class C addresses
  - IP forwarding operation
    - Across networks based upon IP addresses
    - Within networks based upon link layer addresses

Example: Routing Information Protocol (RIP)

- Protocol-inherent problems for Distance Vector routing
  - Limit the applicability to larger networks
- Datagram-based route reporting
  - # items to report vs. MTU size
  - Incremental reporting: all routes need to be sent once every 30s
    - Impact on convergence: impossible to tell the absence of an entry
- Bandwidth requirements for updating
- Instability during routing changes
  - Convergence to a new consistent view of the network takes a while
  - Temporary path unavailability or loops observable from the endpoints
- Counting to infinity
  - Need to define infinity so that converging does not take too long
  - Choice: 16!
  - Hard limit on network diameter

Scaling to Large Number (4): Degradation

- Accuracy requirements may change depending on the number of involved entities
  - Phone conversation vs. small group discussion vs. lecture vs. concert
  - But: distributed database transactions
- Possible tradeoffs
  - Completeness: not all information (state) may need to be known
    - Select representatives
    - Allow for incomplete views
  - Timeliness: state changes may not need to be communicated immediately
    - Allow temporary inaccuracies
  - Functionality: not all operations make sense for all group sizes
    - Example: Repairing packet losses in a TV broadcast with 1 M receivers vs. repairing packet losses in a three party conference
- “Loose coupling”

Example: RTCP

- Provides group membership and reception quality information for RTP sessions
- Must scale with the number of group members
  - Must not take up too much network capacity (rate-limited!)
- Overall “RTP session bandwidth”
- Default: 5% of the session bandwidth for RTCP
  - Takes role (sender or receiver) into account
  - Up to 25% of session members are senders: 3.75% for receivers, 1.25% for senders
  - More than 25% of session members are senders: share data rate proportionally
- Scalable RTCP transmission interval
  - Based upon the group size, RTCP data rate, average RTCP packet size
  - Independently observed by all receivers → calculate their own rate
    - Randomization to avoid synchronization over time
    - Timer reconsideration in case many nodes enter or leave in parallel
  - Default minimum: 5s (2.5 seconds for initial packet)

Scaling to Small and Large Numbers (5)

- Careful choice of field sizes and constants required
  - Avoid fixing if possible
  - If necessary, use foresight (tradeoff: overhead vs. longevity)
- Examples for limiting field sizes and structure
  - 32 bit IPv4 address and its initial (wasteful) address classes
  - IPv4 option space
  - TCP window size (see above)
  - TCP header extension space
  - Port number size (16 bits) and the range allocation (only 16 K dynamic ports)
- Examples for constants
  - 16 = infinity in RIP
  - Initial RTCP timer, minimal RTCP interval

Delegation and Roles

- Distinct roles with different responsibilities for protocol entities
  - Motivated by system/network design, efficient protocol operation, robustness
  - Explicitly assigned (by configuration) vs. self-organizing (inside the protocol)
- Supports division of tasks and helps limiting complexity
- Examples
  - OSPF: Designated Router and Backup Designated Router for stub networks
    - Only one router is responsible for forwarding packets
    - Similar concepts for multicasting
  - IGMP: Designated Querier for IGMP membership polling
  - Peer-to-Peer systems: supernodes vs. regular nodes
  - Reliable Multicasting: Repair heads, DLRs, Repetitors for local repair (packet retransmission) in subgroups or subtrees
  - Multicast Congestion Control: Current Limiting Receiver (CLR) or Selected ACKer to determine acceptable transmission rate

Concluding Remarks

- Scalability means adaptivity
  - “Optimization” problem for multiple input and output parameters
  - Adaptation works only in the order of RTT
  - Beware of oscillation
  - Tradeoff in various dimensions
  - But: Don’t let your protocol get too complex
    - Must be implemented after all
- Scale as you need!
  - But be aware of your requirements
- When you don’t know what to expect: be conservative