Detour: Implementation principles

Goals:
- Identify, study principles that can guide implementation of network protocols
  - Common principles among many protocols
- Synthesis: Big picture

3 classes of principles:
- System principles
- Improving efficiency while retaining modularity
- Making it go fast

Cautionary tales: Think twice
P1: Avoid *obvious* waste in common situations

Obvious waste occurs when one does something twice, but (with thought) could do it only one (or never)

- Copy received data from network interface into OS memory
- Copy data from OS memory into user memory

Diagram:
- User context
- Operating system
- Network interface (buffers)
- Pkts
P1: Avoid *obvious* waste in common situations

- Obvious waste occurs when one does something twice, but (with thought) can do it only once (or never)

![Diagram visualizing the connection between user context, operating system, network interface, zero copy architecture, and buffers with pointers and pkts](image-url)
P2a: Use precomputation to shift computation in time

- Precompute quantities to save time at the point of use
  - Precompute/initialize packet headers for packets in a connection
  - Stored video data to be streamed to client:
    Store video data on disk prepackaged into IP packets. Finish filling out packet header when sending

Real-world examples?
  - 
  - 
  -
P2b: Lazy evaluation: Only do work when it is needed

- Postpone work in hope not needed later, or more time later to do the work. Examples:
  - Data arrives in wrong byte ordering (e.g., big-endian, on little endian machine): Only swap bytes when data actually read (savings if some bytes not read)
  - Copy-on write:

```
address space A

Copy everything then use: byte-by-byte copy

address space B
```
P2b: Lazy evaluation: Only do work when it is needed

Real world examples

- Students reading assigned readings: “Lazy evaluation” says do the reading only if it is on a homework!
Process work (e.g., packet processing) in batches to amortize setup overhead

Example:
- When processing data “up” (or “down”) protocol stack, do multiple packets from connection at same time

Real-world example:
- Sending a bunch of printouts to print room at once (only one trip over)
- Laundry – you don’t do it every day!
- Factory: Make a lot of one item at a time to only incur machine setup costs once
P3a: Trading certainty for time

- If a deterministic approach is too slow, try a randomized approach
  - Random access protocols (Ethernet)
  - Statistical sampling of packet flows

Real-world examples?
- Sampling customers (surveying)
- Shopping schedule: Too much of a hassle to go shopping every sat morning so buy takeout for dinner
P3b: Trading accuracy for time

- If computing the exact result is too slow, maybe an approximate solution will do
  - Optimal solutions may be hard: Heuristics will do
    (e.g., optimal multicast routing is a Steiner tree problem)
  - Faster compression using “lossy” compression
    - Lossy compression: Decompression at receiver will not exactly recreate original signal
  - Hot potato routing

Real-world examples?
- Managing budget
- Quality/time tradeoff: Decreasing marginal returns:
  A 90% solution is good enough. Go one and do the next thing once you’re 90% there
P4: Leverage other system components

- Network protocols run in computing context:
  - Lay out data structures and implement algorithms to enhance caching effects
  - Realize memory is pages, lay out data structures to not cross page boundaries

- Trade memory for speed: Use precomputed lookup tables to get a value, rather than computing on fly each time

Real-world examples?
  - Precompute answers to questions at a press conference or talk ahead of time
P5: Throw hardware at the problem

- Special-function hardware: CRC calculation, encryption
- Export processing functions “off-board”
  - Network-interfaces
- Parallelize protocol functions
  - Parallelized protocols (by layer, by connection, by packet)

thread per layer  
thread per connection
P6: Replace inefficient general-purpose routines
P7: Avoid unnecessary generality

- one-size fits all can lead to inefficiencies
- by specializing, can gain performance (at cost of code bloat)
  - TCP bundles congestion control and error control. What if you want congestion control but don’t care about error control (e.g., real-time delivery of multimedia data)
  - other example: ATM cell size (optimized for voice but used for lots of other types of traffic)
  - but then why do we have only a small number of protocols/approaches at each layer?

real-world examples
  - help lines: treat you like a dummy, takes time to get specialized assistance.
  - standardized pants
Specifications indicate external effects/interaction of protocol.

How protocol is implemented is up to designer

Programming language specifications: In addition to specifying *what*, tend to suggest *how*.

Real-world example:

Recipe:

1. Cut onions
2. Cut potatoes
3. Put onion and potatoes into pot and boil

Steps 1 and 2 can obviously be interchanged......
P9: Pass information, such as hints, across interfaces
P10: Pass information in protocol headers

- Hints: Additional information that, if correct, can improve protocol performance/processing

- P10 example:
  - Each arriving TCP segment contains the receiver-side memory location for the TCP connection record for that segment
  - Receiver initially passes this information to sender, sender includes in all subsequent segments
  - Receiver can find TCP connection records in future without lookup

Real-world examples:
- Letters of recommendation
- Passing information to sales people (order #, phone #) before actual conversations allows them to prefetch all data
P11: Optimize for the expected case

- Future system behavior often (but not always) follows expected pattern. Protocol processing sped up by assuming common case happens

  **Example 1:** Assume next arriving packet at receiver is from same connection as previous one
  - Keep pointer to last accessed TCP connection record, check that one first before searching connection record list

  **Example 2:** Assume TCP segments arrive in order
  - Can answer question: “is this packet in order?” faster than “is this packet in my receiver window?”
  - Keep pointer to last byte copied into user’s socket buffer, next in-order byte will follow that
**P11**: Optimize for the expected case

**Real world examples:**

- **Service lines (e.g., help desks):** Expect that user is novice (common case). If you know what you’re doing, it takes longer to get help.

- **Remote controls and user interfaces:** common functions are fast and easy
P12: Add or exploit state to gain speed

- Maintain state so that you don’t have to compute something every time

- Example: Resource allocation
  - Keep track of resources allocated so know what is free (alternative: go around to all resource users, compute what is being used. What not used is free

Real world example:
- Checking account balance
P13: Optimize degrees of freedom

P14: Use special techniques with small sets of values

P15: Use algorithmic techniques
Some cautionary tales

Q1: Is it worth improving performance?
- Does performance increase have high complexity cost?
- KISS: keep it simple silly
- E.g., router has so many protocols. Would routers be more “robust” if there were fewer protocols?

Q2: Is this really a bottleneck?
- 80% of gains achievable by focusing on 20% of system
- Use profiling tools to see where time is spent
Some cautionary tales

Q3: Effect of change on rest of system?
- Does change increase performance in one place but slow down in other places?

Q4: Does an initial analysis indicate potential significant improvement is possible?
- Is there room for improvement?
- How close to best possible performance? Think about bounds, solutions (e.g., oracle) with unachievable performance
Some cautionary tales

Q5: Is it worth adding custom hardware?
- Ride Moore’s curve (doubling of processing speed every 18 months) or use specialized hardware?

Q6: Can protocol changes be avoided?
- Rather than scrap existing protocol, tweak/rethink it to solve problem?
- Example: TCP’s imminent demise predicted many times (e.g., TCP too slow for high-speed implementation)
Some cautionary tales

Q7: Does prototype confirm initial promise?
- Initial high-level analysis will miss details that could be important
- Some people will never be convinced without an implementation

Q8: Will performance gains be lost if environment changes?
- Think about if improvements limited to small number of environments
- Example: Same-connection, in-order packet assumptions won’t hold in busy server.
Any missing cautionary tales?

- Make sure no one else has done it
  - Corollary: If you have thought it up, it’s likely that someone else has (or will soon) too
- Stress: complexity versus performance tradeoff: what really matters?
- Evaluate benefits under meaningful conditions
Radia Perlman’s Folklore of protocol design

- Collect various tricks and "gotchas" in protocol design.
- "Here are several ways to solve problem X", with technical explanation of pros/cons
- Some “real world” examples

We’ll cover most, not all, “tricks and gotchas”
Simplicity vs. flexibility versus optimality

- Is a more complex protocol reasonable?
- Is “optimal” important?
- **KISS**: “The simpler the protocol, the more likely it is to be successfully implemented and deployed.”

Why are protocols overly complex?

- Design by committee
- Backward compatibility
- Flexibility: Heavyweight swiss army knife
- Unreasonable striving for optimality
- Underspecification
- Exotic/unneeded features

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**Charles Mingus**

“Making the simple complicated is commonplace; making the complicated simple, awesomely simple, that’s creativity!”
More folklore/advice:

Know the problem you are trying to solve:
- Have at least one well-defined problem in mind
- Solve other problems without complicating solution?

Think about scaling
- Think about what happens if you’re successful: protocol is used by millions
- Does the protocol make sense in small situations as well?
More folklore/advice:

Operation above capacity
- Protocol should degrade gracefully in overload, at least detect overload and complain
- How does protocol break and die?
- Can’t just die under overload

Identifiers: Two approaches
- Highly encoded universal IDs: E.g., upper layer protocol # assigned by IANA
- General purpose object identifiers, as in ASN.1
**SNMP naming**

**Question:** How to name every possible standard object (protocol, data, more..) in every possible network standard??

**Answer:** *ISO Object Identifier tree:*

- Hierarchical naming of all objects
- Each branch point has name, number

```
1.3.6.1.2.1.7.1
  ISO
  US DoD
  Internet
  udpInDatagrams
  UDP
  MIB2
  management
```
OSI Object Identifier Tree

Check out www.alvestrand.no/harald/objectid/top.html
## Assigned Internet Protocol numbers

From RFC 1700:

<table>
<thead>
<tr>
<th>Decimal</th>
<th>Keyword</th>
<th>Protocol</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Reserved</td>
<td>Reserved</td>
<td>[JBP]</td>
</tr>
<tr>
<td>1</td>
<td>ICMP</td>
<td>Internet Control Message</td>
<td>[RFC792, JBP]</td>
</tr>
<tr>
<td>2</td>
<td>IGMP</td>
<td>Internet Group Management</td>
<td>[RFC1112, JBP]</td>
</tr>
<tr>
<td>3</td>
<td>GGP</td>
<td>Gateway-to-Gateway</td>
<td>[RFC823, MB]</td>
</tr>
<tr>
<td>4</td>
<td>IP</td>
<td>IP in IP (encapsulation)</td>
<td>[JBP]</td>
</tr>
<tr>
<td>5</td>
<td>ST</td>
<td>Stream</td>
<td>[RFC1190, IEN119, JWF]</td>
</tr>
<tr>
<td>6</td>
<td>TCP</td>
<td>Transmission Control</td>
<td>[RFC793, JBP]</td>
</tr>
<tr>
<td>7</td>
<td>UCL</td>
<td>UCL</td>
<td>[PK]</td>
</tr>
<tr>
<td>8</td>
<td>EGP</td>
<td>Exterior Gateway Protocol</td>
<td>[RFC888, DLM1]</td>
</tr>
<tr>
<td>9</td>
<td>IGP</td>
<td>any private interior gateway</td>
<td>[JBP]</td>
</tr>
<tr>
<td>10</td>
<td>BBN-RCC-MON</td>
<td>BBN RCC Monitoring</td>
<td>[SGC]</td>
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<tr>
<td>11</td>
<td>NVP-II</td>
<td>Network Voice Protocol</td>
<td>[RFC741, SC3]</td>
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<td>12</td>
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<td>[RWS4]</td>
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<td>[BN7]</td>
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<tr>
<td>15</td>
<td>XNET</td>
<td>Cross Net Debugger</td>
<td>[IEN158, JFH2]</td>
</tr>
</tbody>
</table>
More folklore/advice:

Optimize for common case

- Seen this before...
- Nice example: IPV6 payload (packet) length field

- Payload length: 2 bytes
- If packet longer: payload length = 0
- 4 byte length field found in IP options
- Designers chose against 4-byte header to optimize common case: 2 bytes are enough

<table>
<thead>
<tr>
<th>ver</th>
<th>pri</th>
<th>flow label</th>
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<tr>
<td></td>
<td></td>
<td>payload len</td>
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<tr>
<td></td>
<td></td>
<td>source address (128 bits)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>destination address (128 bits)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>data</td>
</tr>
</tbody>
</table>

32 bits
More folklore/advice:

Forward compatibility
- Think about future changes, evolution
- Make fields large enough
- Reserve some spare bits
- Specify an options field that can be used/augmented later

Parameters
- Protocol parameters can be useful
  - Designers can’t determine reasonable values
  - Tradeoffs exist: Leave parameter choice to users
- Parameters can be bad
  - Users (often not well informed) will need to choose values
  - Try to make values plug-and-play
Making systems “robust”: Many forms of robustness

- Immediately adapt to failure/change
- Self-stabilization: Eventually adapt to failure/change
- Byzantine robustness: Will work in spite of malicious users

- Maybe better to crash than degrade when problems occur: Signal problem exists
- Techniques for limited spread of figures
Missing folklore/advice:
The end: Implementation principles

Goals:
- Identify, study principles that can guide implementation of network protocols
  - Common principles among many protocols
  - “Folklore” of protocol design
- Synthesis: Big picture
- Architecture and implementation: Both more art than science