Objectives

• Why do good technology ideas fail?
• What are different kinds of research?
• Why do networks increase in complexity?
• What does network traffic look like?
• How have network costs change?
• What are the economic trade-offs between computing, communication and storage?
• What are other network models besides the “classical” Internet?
## Cause of death for the next big thing

<table>
<thead>
<tr>
<th></th>
<th>QoS</th>
<th>multicast</th>
<th>mobile IP</th>
<th>active networks</th>
<th>IPsec</th>
<th>IPv6</th>
</tr>
</thead>
<tbody>
<tr>
<td>not manageable across competing domains</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td></td>
</tr>
<tr>
<td>not configurable by normal users (or apps writers)</td>
<td>✅</td>
<td></td>
<td></td>
<td>✅</td>
<td></td>
<td>✅</td>
</tr>
<tr>
<td>no business model for ISPs</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td></td>
<td>✅</td>
</tr>
<tr>
<td>no initial gain</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80% solution in existing system</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td></td>
<td>(NAT)</td>
</tr>
<tr>
<td>increase system vulnerability</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Why do good ideas fail?

- Research: O(.), CPU overhead
  - “per-flow reservation (RSVP) doesn’t scale” → not the problem
    - at least now -- routinely handle O(50,000) routing states

- Reality:
  - deployment costs of any new L3 technology is probably billions of $

- Cost of failure:
  - conservative estimate (1 grad student year = 2 papers)
  - 10,000 QoS papers @ $20,000/paper → $200 million
Research: Network evolution

- Only three modes, now thoroughly explored:
  - packet/cell-based
  - message-based (application data units)
  - session-based (circuits)
- Replace specialized networks
  - left to do: embedded systems
    - need cost(CPU + network) < $10
    - cars
    - industrial (manufacturing) control
    - commercial buildings (lighting, HVAC, security; now LONworks)
    - remote controls, light switches
    - keys replaced by biometrics
Research: Pasteur’s quadrant

<table>
<thead>
<tr>
<th>Quest for Fundamental Understanding?</th>
<th>Considerations of Use?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Pure basic research (Bohr)</td>
</tr>
<tr>
<td>No</td>
<td>Use-inspired basic research (Pasteur)</td>
</tr>
<tr>
<td>No</td>
<td>Guessing at problems (Infocom)</td>
</tr>
<tr>
<td>Yes</td>
<td>Pure applied research (Edison)</td>
</tr>
</tbody>
</table>

Most networking research wants to be here

Most networking research is here

*Pasteur’s Quadrant: Basic Science and Technological Innovation, Stokes 1997 (modified)*
Maturing network research

• Old questions:
  • Can we make X work over packet networks?
    • All major dedicated network applications (flight reservations, embedded systems, radio, TV, telephone, fax, messaging, …) are now available on IP
  • Can we get M/G/T bits/s to the end user?
  • Raw bits everywhere: “any media, anytime, anywhere”

• New questions:
  • Dependency on communications → Can we make the network reliable?
  • Can non-technical users use networks without becoming amateur sysadmins? → auto/zeroconfiguration, autonomous computing, self-healing networks, …
  • Can we make networks affordable to everyone?
  • Can we prevent social and financial damage inflicted through networks (viruses, spam, DOS, identity theft, privacy violations, …)?
New applications

• New bandwidth-intensive applications
  • Reality-based networking
  • (security) cameras ➔ “ambient video”
• New bandwidth-extensive applications
  • communicate infrequently ➔ setup overhead
  • SIGFOX network
• Distributed games often require only low-bandwidth control information
  • current game traffic ~ VoIP
  • 4G, 5G ➔ low latency
• Computation vs. storage vs. communications
  • communications cost has decreased less rapidly than storage costs

SIGFOX (902 MHz, 100 bps) is a connectivity solution that focuses on low throughput devices. On SIGFOX you can send between 0 and 140 messages per day and each message can be up to 12 bytes of actual payload data.
Change is hard

- No new network services deployed since 1980s
  - universal upgrade
  - chicken/egg (network/OS) problem
- “Innovation at edges”
- Applications easier, as long as
  - TCP-based
  - client-server
  - … but there are exceptions (p2p)
# Time of transition

<table>
<thead>
<tr>
<th>Old</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPv4</td>
<td>IPv6</td>
</tr>
<tr>
<td>circuit-switched voice</td>
<td>VoIP</td>
</tr>
<tr>
<td>separate mobile voice &amp; data</td>
<td>LTE + LTE-VoIP</td>
</tr>
<tr>
<td>911, 112</td>
<td>NG911, NG112</td>
</tr>
<tr>
<td>digital cable (QAM)</td>
<td>IPTV</td>
</tr>
<tr>
<td>analog &amp; digital radio</td>
<td>Pandora, Internet radio, satellite radio</td>
</tr>
<tr>
<td>credit cards, keys</td>
<td>NFC</td>
</tr>
<tr>
<td>end system, peers</td>
<td>client-server v2 aka cloud</td>
</tr>
</tbody>
</table>

all the energy into transition ➔ little new technology
Technology transition

research

standards

products

de-facto standards

protocols vs. algorithms!
Internet challenges

- IP address depletion
- NAT, middle boxes and the loss of transparency
- Routing infrastructure
- Quality of service
- Security
  - old protocols
  - key and trust management difficult
- DNS scaling
- Dealing with privatization
- Interplanetary Internet
COMPLEXITY
Mid-Life Crisis

- doubles number of service interfaces
- requires changes above & below
- major interoperability issues
“Why architectural complexity is like body fat”

- You naturally tend to gain it while you grow older
- Very easy to gain and very hard to get rid of
  - Designing complex solutions and protocols easier than designing simple ones.
- Healthy to have some, but not too much
- Having it on waist may be worse than elsewhere
- Younger and slimmer will eventually beat you
  - Architectural complexity → reduced agility → younger and less complex systems eventually replace older and more complex system.
- Sometimes surgery is a good way to start
- Long term results require constant exercise

http://www.tml.tkk.fi/~pnr/FAT/
Causes of complexity

- Complexity: implementation vs. run-time
  - system vs. protocol
- After-the-fact enhancements:
  - security
  - NAT traversal
  - mobility
  - internationalization (e.g., DNS)
- Wrong layer for function
  - multicast? IP security?
- Options
  - e.g., multiple transport protocols, IPv4 & IPv6
- Lots of special protocols
  - e.g., IMAP, POP, SMTP
- Manual configuration
Mobile traffic distribution – 2011 prediction

Petabytes per Month

2010 2011 2012 2013 2014 2015

VoIP traffic forecasted to be 0.4% of all mobile data traffic in 2015.
Source: Cisco VNI Mobile, 2011
Mobile traffic distribution – 2014 prediction

Overall mobile data traffic is expected to grow to 15.9 exabytes per month by 2018, nearly an 11-fold increase over 2013. Mobile data traffic will grow at a CAGR of 61 percent from 2013 to 2018 (Figure 1).

Figure 1. Cisco Forecasts 15.9 Exabytes per Month of Mobile Data Traffic by 2018

The Asia Pacific and North America regions will account for almost two-thirds of global mobile traffic by 2018, as shown in Figure 2. Middle East and Africa will experience the highest CAGR of 70 percent, increasing 14-fold over the forecast period. Central and Eastern Europe will have the second highest CAGR of 68 percent, increasing 13-fold over the forecast period. The emerging market regions of Asia Pacific and Latin America will have CAGRs of 67 percent and 66 percent respectively.

Source: Cisco VNI Mobile, 2014
Mobile traffic is mostly Wi-Fi

As a percentage of total mobile data traffic from all mobile-connected devices, mobile offload increases from 45 percent (1.2 exabytes/month) in 2013 to 52 percent (17.3 exabytes/month) by 2018 (Figure 14). Without offload, Global mobile data traffic would grow at a CAGR of 65 percent instead of 61 percent. Offload volume is determined by smartphone penetration, dual-mode share of handsets, percentage of home-based mobile Internet use, and percentage of dual-mode smartphone owners with Wi-Fi fixed Internet access at home.

Figure 14. 52 Percent of Total Mobile Data Traffic Will Be Offloaded by 2018

The amount of traffic offloaded from smartphones will be 51 percent by 2018, and the amount of traffic offloaded from tablets will be 69 percent by 2018.

A supporting trend is the growth of cellular connectivity for devices such as tablets which in their earlier generation were limited to Wi-Fi connectivity only. With increased desire for mobility and mobile carriers offer of data plans catering to multi-device owners, we find that the cellular connectivity is on a rise albeit cautiously as the end users are testing the waters. As a point in case, we estimate that by 2018, 42 percent of all tablets will have a cellular connection up from 34 percent in 2013 (Figure 15).

Source: Cisco VNI Mobile, 2014
Figure 10. Mobile Video Will Generate Over 69 Percent of Mobile Data Traffic by 2018

Because many Internet video applications can be categorized as cloud applications, mobile cloud traffic follows a curve similar to video. Mobile devices have memory and speed limitations that might prevent them from acting as media consumption devices, were it not for cloud applications and services. Cloud applications and services such as Netflix, YouTube, Pandora, and Spotify allow mobile users to overcome the memory capacity and processing power limitations of mobile devices. Globally, cloud applications will account for 90 percent of total mobile data traffic by 2018, compared to 82 percent at the end of 2013 (Figure 11). Mobile cloud traffic will grow 12-fold from 2013 to 2018, a compound annual growth rate of 64 percent.

Exabytes per Month

61% CAGR 2013-2018

- Mobile File Sharing (2.9%)
- Mobile M2M (5.7%)
- Mobile Audio (10.6%)
- Mobile Web/Data (11.7%)
- Mobile Video (69.1%)

Figures in parentheses refer to traffic share in 2018.
Source: Cisco VNI Mobile, 2014
## Monthly Consumption (fixed)

<table>
<thead>
<tr>
<th>North America</th>
<th>Mean</th>
<th>Median</th>
<th>Mean : Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream</td>
<td>8.5 GB</td>
<td>1.8 GB</td>
<td>4.7</td>
</tr>
<tr>
<td>Downstream</td>
<td>48.9 GB</td>
<td>20.4 GB</td>
<td>2.4</td>
</tr>
<tr>
<td>Aggregate</td>
<td>57.4 GB</td>
<td>22.5 GB</td>
<td>2.6</td>
</tr>
</tbody>
</table>

- **top 1% →**
  - 49.7% of upstream traffic
  - 25% of downstream traffic

<table>
<thead>
<tr>
<th>Europe</th>
<th>Mean</th>
<th>Median</th>
<th>Mean : Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream</td>
<td>5.1 GB</td>
<td>1.5 GB</td>
<td>3.4</td>
</tr>
<tr>
<td>Downstream</td>
<td>23.1 GB</td>
<td>8.7 GB</td>
<td>2.7</td>
</tr>
<tr>
<td>Aggregate</td>
<td>28.2 GB</td>
<td>10.1 GB</td>
<td>2.8</td>
</tr>
</tbody>
</table>
The value of bits

- Technologist: A bit is a bit is a bit
- Economist: Some bits are more valuable than other bits
  - e.g., $(email) >> $(video)

<table>
<thead>
<tr>
<th>Application</th>
<th>Volume</th>
<th>Cost per unit</th>
<th>Cost / MB</th>
<th>Cost / TB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice (13 kb/s GSM)</td>
<td>97.5 kB/minute</td>
<td>10c</td>
<td>$1.02</td>
<td>$1M</td>
</tr>
<tr>
<td>Mobile data</td>
<td>5 GB</td>
<td>$40</td>
<td>$0.008</td>
<td>$8,000</td>
</tr>
<tr>
<td>MMS (pictures)</td>
<td>&lt; 300 KB, avg. 50 kB</td>
<td>25c</td>
<td>$5.00</td>
<td>$5M</td>
</tr>
<tr>
<td>SMS</td>
<td>160 B</td>
<td>10c</td>
<td>$625</td>
<td>$625M</td>
</tr>
</tbody>
</table>
## Video, video and more video

<table>
<thead>
<tr>
<th>Upstream</th>
<th>Downstream</th>
<th>Aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>BitTorrent</td>
<td>52.01%</td>
<td>Netflix</td>
</tr>
<tr>
<td>BitTorrent</td>
<td>29.70%</td>
<td>Netflix</td>
</tr>
<tr>
<td>BitTorrent</td>
<td>24.71%</td>
<td></td>
</tr>
<tr>
<td>HTTP</td>
<td>8.31%</td>
<td>HTTP</td>
</tr>
<tr>
<td>HTTP</td>
<td>18.36%</td>
<td>BitTorrent</td>
</tr>
<tr>
<td>HTTP</td>
<td>17.23%</td>
<td></td>
</tr>
<tr>
<td>Skype</td>
<td>3.81%</td>
<td>YouTube</td>
</tr>
<tr>
<td>Skype</td>
<td>11.04%</td>
<td>HTTP</td>
</tr>
<tr>
<td>Skype</td>
<td>17.18%</td>
<td></td>
</tr>
<tr>
<td>Netflix</td>
<td>3.59%</td>
<td>BitTorrent</td>
</tr>
<tr>
<td>Netflix</td>
<td>10.37%</td>
<td>YouTube</td>
</tr>
<tr>
<td>Netflix</td>
<td>9.85%</td>
<td></td>
</tr>
<tr>
<td>PPStream</td>
<td>2.92%</td>
<td>Flash Video</td>
</tr>
<tr>
<td>PPStream</td>
<td>4.88%</td>
<td>Flash Video</td>
</tr>
<tr>
<td>PPStream</td>
<td>3.62%</td>
<td></td>
</tr>
<tr>
<td>MGCP</td>
<td>2.89%</td>
<td>iTunes</td>
</tr>
<tr>
<td>MGCP</td>
<td>3.25%</td>
<td>iTunes</td>
</tr>
<tr>
<td>MGCP</td>
<td>3.01%</td>
<td></td>
</tr>
<tr>
<td>RTP</td>
<td>2.85%</td>
<td>RTMP</td>
</tr>
<tr>
<td>RTP</td>
<td>2.92%</td>
<td>RTMP</td>
</tr>
<tr>
<td>RTP</td>
<td>2.46%</td>
<td></td>
</tr>
<tr>
<td>SSL</td>
<td>2.75%</td>
<td>Facebook</td>
</tr>
<tr>
<td>SSL</td>
<td>1.91%</td>
<td>Facebook</td>
</tr>
<tr>
<td>SSL</td>
<td>1.86%</td>
<td></td>
</tr>
<tr>
<td>Gnutella</td>
<td>2.12%</td>
<td>SSL</td>
</tr>
<tr>
<td>Gnutella</td>
<td>1.43%</td>
<td>SSL</td>
</tr>
<tr>
<td>Gnutella</td>
<td>1.68%</td>
<td></td>
</tr>
<tr>
<td>Facebook</td>
<td>2.00%</td>
<td>Hulu</td>
</tr>
<tr>
<td>Facebook</td>
<td>1.09%</td>
<td>Skype</td>
</tr>
<tr>
<td>Facebook</td>
<td>1.29%</td>
<td></td>
</tr>
<tr>
<td>Top 10</td>
<td>83.25%</td>
<td>Top 10</td>
</tr>
<tr>
<td>Top 10</td>
<td>84.95%</td>
<td>Top 10</td>
</tr>
<tr>
<td>Top 10</td>
<td>82.89%</td>
<td></td>
</tr>
</tbody>
</table>
Average monthly usage

- Average monthly TV consumption (US): 154 hours
- Netflix: 1 GB/hour (SD) … 2.3 GB/hour (HD)
  - → 300 GB/month
  - more if people in household watch different content

<table>
<thead>
<tr>
<th>monthly usage</th>
<th>overage cost (AT&amp;T Uverse)</th>
<th>2010</th>
<th>2012</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 50 GB</td>
<td>$0</td>
<td>9.4%</td>
<td>14.1%</td>
<td>21.5%</td>
</tr>
<tr>
<td>&gt; 100 GB</td>
<td>$0</td>
<td>5.3%</td>
<td>8.2%</td>
<td>15.3%</td>
</tr>
<tr>
<td>&gt; 200 GB</td>
<td>$10</td>
<td>1.4%</td>
<td>4.4%</td>
<td>8.8%</td>
</tr>
<tr>
<td>&gt; 500 GB</td>
<td>$50</td>
<td>0.4%</td>
<td>0.8%</td>
<td>2.6%</td>
</tr>
<tr>
<td>&gt; 1 TB</td>
<td>$150</td>
<td>0.0%</td>
<td>0.2%</td>
<td>0.7%</td>
</tr>
</tbody>
</table>
Bandwidth generations

Source: Cisco VNI, 2011
Transit prices

$/Mbps

http://drpeering.net/white-papers/Internet-Transit-Pricing-Historical-And-Projected.php
Cost of bandwidth

Fig. 5: SONET/SDH vs. Ethernet Monthly Cost

Backbone DWDM per-bit, per-km cost improvements over time

Figure 1

Source: Ovum
Bandwidth costs

- Amazon EC2
  - $50 - $120/TB out, $0/TB in
- CDN (Internet radio)
  - $600/TB (2007)
  - $7-20/TB (Q1 2014 – CDNpricing.com)
- Netflix (7 GB DVD)
  - postage $0.70 round-trip → $100/TB
- FedEx – 2 lb disk
  - 5 business days: $6.55
  - Standard overnight: $43.68
  - Barracuda disk: $30 - $60/TB (2015)
- DVD-R (7 GB)
  - $0.25/disk → $35/TB
### Cost of bandwidth (2011 & 2015)

<table>
<thead>
<tr>
<th>Service</th>
<th>Speed (Mb/s)</th>
<th>Average price/ month 2015 (2011)</th>
<th>$/Mb/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS1 (T1)</td>
<td>1.54</td>
<td>$295 ($450)</td>
<td>$197 ($292)</td>
</tr>
<tr>
<td>DS3</td>
<td>45</td>
<td>$1950 ($5,000)</td>
<td>$43 ($111)</td>
</tr>
<tr>
<td>Ethernet over Copper</td>
<td>10</td>
<td>$310 ($950)</td>
<td>$31 ($95)</td>
</tr>
<tr>
<td>Fast Ethernet</td>
<td>100</td>
<td>$1,800 ($5,000)</td>
<td>$18 ($50)</td>
</tr>
<tr>
<td>Gigabit Ethernet</td>
<td>1000</td>
<td>$4,000 ($25,000)</td>
<td>$4 ($25)</td>
</tr>
</tbody>
</table>
NETWORK REALITY
## Textbook Internet vs. real Internet

<table>
<thead>
<tr>
<th>Ideal</th>
<th>Reality</th>
</tr>
</thead>
<tbody>
<tr>
<td>end-to-end (application only in 2 places)</td>
<td>middle boxes (proxies, ALGs, …)</td>
</tr>
<tr>
<td>permanent interface identifier (IP address)</td>
<td>time-varying (DHCP, mobile)</td>
</tr>
<tr>
<td>globally unique and routable</td>
<td>network address translation (NAT)</td>
</tr>
<tr>
<td>multitude of L2 protocols (ATM, ARCnet, Ethernet, FDDI, modems, …)</td>
<td>dominance of Ethernet, but also L2’s not designed for networks (1394 Firewire, Fibre Channel, MPEG2, …)</td>
</tr>
</tbody>
</table>
### Textbook Internet vs. real Internet

<table>
<thead>
<tr>
<th>Mostly trusted end users</th>
<th>Hackers, spammers, con artists, pornographers, …</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small number of manufacturers, making expensive boxes</td>
<td>Linksys, Dlink, Netgear, …, available at Walmart</td>
</tr>
<tr>
<td>Technical users, excited about new technology</td>
<td>Grandma, frustrated if email doesn’t work</td>
</tr>
<tr>
<td>4 layers (link, network, transport, application)</td>
<td>Layer splits</td>
</tr>
<tr>
<td>Transparent network</td>
<td>Firewalls, L7 filters, “transparent proxies”</td>
</tr>
</tbody>
</table>
Which Internet are you connected to?

- QoS
- IPv6
- IPv4
- PIA
- multicast
- IPv4 NAT
- IPv4 DHCP
- port 80 + 25
The two-port Internet

- Many public access systems only allow port 80 (HTTP) and maybe 25 (SMTP)
  - e.g., public libraries
- Everything tunneled over HTTP
  - Web-based email
  - Video delivery (e.g., YouTube, Netflix)
  - HTTP CONNECT for remote login
Causes

• Link-layer technologies
  • satellite, DSL
  • NBMA

• Network-layer technologies
  • security: broken by design vs. broken by accident?
  • NATs
  • Ill-defined meaning of IP addresses and names
    • theoretically, single network interface
    • practically, often more than that
      • virtualization
      • multi-homing
      • fail-over
Private Internet -- challenges

- Public Internet = collection of privately-owned (mostly) for-profit networks
- Incentives for greedy behavior
- Special-purpose networks
  - VoIP networks
  - 3GPP, NGN, … ➔ “walled garden”
  - sub-applications large enough to support own infrastructure
- Private protocols
  - e.g., most IM protocols
- Patent encumbrances
  - see https://datatracker.ietf.org/public/ipr_disclosure.cgi
- D. Clark, J. Wroclawski, K. Sollins, R. Braden, “Tussle in Cyberspace: Defining Tomorrow’s Internet”, ToN, June 2005
Tussle in Cyberspace

- Traditional view: design technology to make choices
- Tussle view: design technology to allow choices
  - “we are designing the social contract that the Internet embodies”
  - not a final outcome, on-going process → lawyers vs. engineers
- Multiple competing interests
  - application value capture
    - high value content looks the same to ISP
  - traffic price differentiation
    - willingness to pay
  - investment in infrastructure vs. open interfaces
    - sunk costs
  - greed (local traffic optimization vs. social optimum)
  - privacy and anonymity vs. societal goals
    - CALEA, network resource protection, spam, DRM
- → Allow multiple outcomes, but give users choice (competition)
  - user-selected routes and servers

Other network models

- Interplanetary networks
  - Extremely long round-trip times, large feedback delays
  - Protocols designed with terrestrial timeout parameters
  - See Vint Cerf’s web page and Delay-Tolerant Networking Research Group (DTNRG)

- Disconnected or delay-tolerant operation
  - “store-and-forward” at the content rather than packet level
    - generalized email model?
    - see UUCP

- Sensor networks
  - Extremely lossy links
  - resource-constrained network nodes

- Content-based networks
  - routing based on content hash
## Other network types

<table>
<thead>
<tr>
<th>network</th>
<th>partially disconnected</th>
<th>mobile end systems</th>
<th>wireless links</th>
<th>mobile routers</th>
<th>energy optimization</th>
<th>node computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>“classical” Internet</td>
<td>caching, sync.</td>
<td>fixed nomadic mobile</td>
<td>last hop</td>
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<td>mesh networks</td>
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<tr>
<td>MANET</td>
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<td>only</td>
<td>fast</td>
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<td>delay-tolerant networks</td>
<td>possibly</td>
<td>planets space craft</td>
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<tr>
<td>sensor networks</td>
<td>some systems</td>
<td>yes</td>
<td>common</td>
<td>some</td>
<td>crucial</td>
<td>common</td>
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