THE GEOMORPHIC VIEW OF NETWORKING:
AN ABSTRACT MODEL
AND ITS USES

Pamela Zave
AT&T Laboratories—Research
Bedminster, New Jersey, USA

Joint work with Jennifer Rexford, Princeton University
OUTLINE

1  MOTIVATION FOR AN ABSTRACT MODEL

2  THE “GEOMORPHIC VIEW” OF NETWORKING

3  THE GEOMORPHIC VIEW OF MOBILITY
   a  Two patterns for implementing mobility
   b  A composition theorem
   c  Evaluation of mobility standards

4  FUTURE WORK
THE “CLASSIC” INTERNET ARCHITECTURE

APPLICATION LAYER

TRANSPORT LAYER

NETWORK LAYER

LINK LAYER

PHYSICAL LAYER
A REAL PROTOCOL STACK

headers in a typical AT&T packet (12 instead of 4)

<table>
<thead>
<tr>
<th>Application</th>
<th>HTTP</th>
<th>TCP</th>
<th>IP</th>
<th>IPsec</th>
<th>IP</th>
<th>GTP</th>
<th>UDP</th>
<th>IP</th>
<th>MPLS</th>
<th>MPLS</th>
<th>Ethernet</th>
</tr>
</thead>
</table>

HTTP being used as a transport protocol because it is the only way to traverse NAT boxes and firewalls

security

cellular service (mobility, QoS, billing)

15 + load-balancing algorithms operate on this packet, most of them understood and tested only in isolation

multiple layers of resource management
The prevailing view in software-defined networking (SDN) to be provided by fine-grained routing:

- virtualization
- mobility
- middlebox services
- security
- multipath routing
- load balancing
- elastic resource allocation
- fault tolerance
- bandwidth guarantees
- latency guarantees

Nick McKeown says:

One of the major benefits of SDN is a well-defined control abstraction . . . so that software engineering can be applied to its implementation.

Software engineering calls for . . .

. . . modularity
. . . separation of concerns
CLASSIC LAYERS OR OSI REFERENCE MODEL

there is a fixed number of layers

each layer has a distinct and indispensable function

THE GEOMORPHIC VIEW OF NETWORKING

each layer is a microcosm of networking, containing all the basic functions (state components and mechanisms)

there can be any number of levels, each with any number of layers

the layers are modules, providing orderly, fine-grained separation of concerns
## Potential Benefits of Layers as Homogeneous Modules

**For Applications**
- Encourage a richer variety of communication services
- Provide well-specified interfaces to these services

**For Research Progress**
- Act as a rigorous description framework in which each proposal has a canonical description, ... allowing proposals to be compared and composed
- Serve as a foundation for formal reasoning, ... especially hierarchical reasoning

**For Design**
- Manage complexity through separation of concerns followed by composition of concerns
- Achieve many diverse goals for diverse stakeholders, all within the same system
- Facilitate recognition of ... recurring patterns ... design principles ... structured trade-off spaces

**For Implementation**
- Implement implicit layers efficiently, but recoverably
- Encourage development of re-usable ... implementation mechanisms ... algorithms for optimization and code generation
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A NEW LAYER MODEL: MEMBERS, ROUTING, AND FORWARDING

A process, which is merely a locus of state and control that can act autonomously within the layer is unique and persistent.

Member

Forwarding protocol enables members to send messages to one another, using the links.

Routes tell the forwarding protocol how to reach one member from another over the existing links, with forwarding by intermediate members.

Routing algorithm maintains the routes as links change over time.
A NEW LAYER MODEL: COMMUNICATION SERVICES

channel an instance of a communication service

session a communication channel (as is a link)

session protocol implements an end-to-end communication service, on top of the basic message delivery provided by the forwarding protocol

from the perspective of the endpoints, sessions are more convenient than links

may have . . . reliability,
. . . FIFO delivery,
. . . security,
. . . and other services
A NEW LAYER MODEL: THE “USES” HIERARCHY

when an overlay uses an underlay, a link in the overlay is implemented by a session in the underlay

possible setup of this link/session:
1. A sends request to a
2. a looks up registration of E, finds e
3. a sends request to e
4. e sends request to E
A NEW LAYER MODEL: MAJOR PARTS

PROTOCOLS

or, the “data plane”

STATE COMPONENTS

or, the “control plane”

can be centralized or distributed across the members in any way

ALGORITHMS

where members are registered in underlays
registrations of overlay members in this layer

members

attachments

locations

there are algorithms to maintain other state components

session protocol

forwarding protocol

sessions

links

routes

routing algorithm
layers are arranged in a “uses” hierarchy, which defines levels

the scope of a layer is the set or class of processes that could be members

APPLICATION LAYERS

INTERNET CORE (IP, TCP, UDP)

LANs

application process

IP interface of machine

gateway

Ethernet interface

this describes the classic Internet architecture

in the real Internet, there are layers at many more levels, for many different purposes
WE CALL THIS THE “GEOMORPHIC VIEW” OF NETWORKING . . .

. . . BECAUSE THE COMPLEX ARRANGEMENT OF LAYERS RESEMBLES THE EARTH’S CRUST
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4. FUTURE WORK
A DEFINITION OF MOBILITY

either endpoint can initiate the channel, provided that both are connected to the network.

persistent link or session

the channel persists even when one or both endpoints changes its connection to the network.

common example: cellphone voice service

wearable health-monitoring device

down the protocol stack

person moves around

device uses both cellular and WiFi connections, alternatively or simultaneously

minimal keep-alive signaling, to reduce battery drain

virtual-machine migration

re-routing around failed links to data center

persistent link supporting periodic monitoring

this is a data service—no application programming needed

personalized data analysis and abnormality alerting

down the protocol stack
A DEFINITION OF MOBILITY, CONTINUED

APPLICATION LAYER

wearable health-monitoring device

persistent link supporting periodic monitoring

personalized data analysis and abnormality alerting

LOWER LAYERS

when a mobile device moves, it changes its attachment to a wireless LAN

when a virtual machine migrates, it changes its attachment to a physical machine

every instance of mobility is a layer member’s change of attachment to a lower layer

related to multihoming, anycast, etc.
A PATTERN FOR IMPLEMENTING MOBILITY

DYNAMIC-ROUTING MOBILITY

BENEFITING LAYER

LAYER IMPLEMENTING MOBILITY

this link connects \textit{a} to the rest of its layer
A PATTERN FOR IMPLEMENTING MOBILITY

DYNAMIC-ROUTING MOBILITY

BENEFITING LAYER

as the attachment of a member changes, its links change, and the routing algorithm must find new routes to it

layer state components that change:

*attachments*
*links*
*routes*

a1

a2
ANOTHER PATTERN FOR IMPLEMENTING MOBILITY

BENEFITING LAYER

SESSION-LOCATION MOBILITY

as part of the session state, a knows b1 as the far endpoint of the session

A

B

a

b1

a2
ANOTHER PATTERN FOR IMPLEMENTING MOBILITY

BENEFITING LAYER

SESSION-LOCATION MOBILITY

as the link endpoint changes its location in the implementing layer, the session state changes to match it

tell \( a \) that session endpoint is now \( b_2 \)

layer state components that change:
- members
- locations
- sessions
Both patterns for implementing mobility

Layer state components that change:
- Attachments
- Links
- Routes

Layer state components that change:
- Members
- Locations
- Sessions
STRENGTHS AND WEAKNESSES OF THE PATTERNS

see our chapter “The design space of network mobility” in the new SIGCOMM eBook

DYNAMIC-ROUTING MOBILITY

Strengths

Works well in a layer with a smaller scope and a flat name space—usually dynamic routing for mobility is no different from “normal” routing.

\[ \text{e.g., Ethernet} \]

Weaknesses

In a larger layer with a hierarchical name space, costs for dynamic routing to individual members are high.

How many routers know where to find a mobile member?

If many, storage and update costs are high

If few, path costs are high

\[ \text{e.g., Mobile IPv4} \]

SESSION-LOCATION MOBILITY

Strengths

Low storage and update costs.

No path costs.

Weaknesses

Requires endpoint involvement, so cannot be deployed without changing endpoint software.

Message losses during handover may be disruptive.
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COMPOSITIONAL NETWORK MOBILITY

- every mobility mechanism specializes one of these patterns, or is a composition of the two

  with enough design freedom, instances of mobility can be moved up and down the levels

- in principle, each instance of mobility could be handled with either of these patterns at any level below the benefiting layer — so mobility mechanisms could be everywhere

  there is a large design space, much of it unexplored

- an interesting question: how do implementations of both patterns in the same layer compose?
AN ACTIVE IMPLEMENTED CHANNEL

c.initiator <-> c.acceptor

c.userLayer

c.implLayer

locInit <-> locAccpt

active active active

locInit <-> locAccpt

c.initFarLoc = locAccpt

c.accptFarLoc = locInit

reachable
MOBILITY COULD DESTROY REGISTRATIONS

AN INACTIVE IMPLEMENTED CHANNEL

MODEL IMPLEMENTS BOTH PATTERNS IN EVERY LAYER

MOBILITY COULD DESTROY OR INACTIVATE LINKS

MOBILITY COULD CAUSE FAR LOCATIONS IN SESSION STATE TO BE WRONG

MODEL IMPLEMENTS BOTH PATTERNS IN EVERY LAYER
We cannot assume that mobile devices and network elements will perform all the requisite actions (to prove a true progress property).

We do assume that a mobile device can always become a member of a layer of its choice.

**Theorem:**

In any state in which an implemented link is inactive, some event is enabled whose execution will make progress toward making the link active (a safety property).

**Proof at one level:**

Manual enumeration of possible event sequences, automated checking of their preconditions with the Alloy Analyzer (verification over small domains).
WHAT COULD GO WRONG?

both endpoints have moved

both endpoints have the wrong far location

either can send an update message to the other
SOME EVENT SEQUENCES

1. CreateRegistration

2. UpdateFarLocFromEndpoint

3. UpdateDirectory

4. UpdateFarLocFromDirectory

in the double-handoff scenario, 1, 2, 3 and 1, 3, 2 do not work, but 1, 3, 4 does.
WHAT DOES THE THEOREM REALLY MEAN?

Events are coarse-grained and probably not implemented atomically.

In real network implementations, the problem is always conflation of concerns.

fields are overloaded, existing mechanisms are “repurposed”, etc.

The theorem provides a set of constraints on independence of events and separation of data . . .

. . . that are sufficient to prove composability of the two patterns.
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EVALUATION OF STANDARDS FOR SESSION-LOCATION MOBILITY

or, how to survive thousands of pages of IETF RFCs

It is a lot easier to read them when you have the pattern in mind and know what you are looking for!

STANDARDS

- Mobile IPv6
- LISP Mobile Node
- HIP
- ILNP

THEIR IDENTIFIERS

- locators are always IP addresses, usually IPv6
- IP addresses
- public keys, or hashes thereof
- 64-bit suffixes of IPv6 addresses, where the locator is the whole address

the “route optimization” mechanism, composed in a complex way with dynamic-routing mobility

a useful afterthought to LISP, whose purpose is not mobility

IETF documents with “experimental” status
LISP Mobile Node is the best for interoperation, best overall

TCP runs unchanged

both proxies are stateless, in path only when needed, and can be located anywhere

the gray areas share an implementation—ordinary IP—with subtle differences

note that only the LISP-MN nodes need to distinguish the two layers
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THE DESIGN SPACE OF CLOUD COMPUTING

HOW CAN THE COMPOSITION OF ALL THESE REQUIREMENTS BE SATISFIED?

SERVICES FOR ENTERPRISE CUSTOMERS

- customizable address space
- services provided by proxies and middleboxes (especially security), with elastic resources
- broadcast domains

GUARANTEES FOR ENTERPRISE CUSTOMERS

- isolation
- quality of service

CLOUD MANAGEMENT

- virtual-machine migration
- multiple data centers
- fault tolerance

INTERESTING OBSERVATION:

Most requirements seem to have two implementations, . . .

. . . one in a routing algorithm, and

. . . one in a session protocol.
NETWORK VERIFICATION AND HEADER-SPACE ANALYSIS

THE GEOMORPHIC VIEW

FLATTENS ALL LAYERS INTO ONE SPACE WHERE COMPUTATION IS DEFINED

ENCOURAGES AND ELUCIDATES SEPARATION OF LAYERS

SOME AREAS OF DIFFICULTY:

- need to discover relevant packet fields and describe their transformations
- important assertions may only be expressible in layers above the base IP layer, or may cross layers
- the flattened space is large and computationally complex

HOW THE GEOMORPHIC VIEW MIGHT HELP:

- these are easier to understand and formalize when layers are separated first
- might allow analysis to be decomposed hierarchically