An Axiomatic Basis for Communication

M. Karsten[1], S. Keshav[1], and S. Prasad[2]
[1]University of Waterloo
[2]IIT Delhi

Did you know that...?

For example:

- NAT = ATM
- DNS: Forwarding overlay
- Source routing is heavily used in the Internet

Outline

- The unreasonable Internet
- The axioms of communication
- Notes on formalization
- Conclusions

The unreasonable Internet

- Original Internet assumptions
  - Static public IP addresses
  - 5-layer stack
  - No layer violations
  - Forwarding based only on IP routing tables

In fact...

- All these assumptions are violated
    - DHCP, NAT, Mobile IP -> dynamic IP
    - Many more layers (VLAN, P2P, MPLS ...)
    - Layering extensively violated (NAT, firewall, DNS redirection)
    - Forwarding based on VLAN ID, MPLS ID, source IP (!)

But...

- It still works
  - mostly
  - for most people
- Why?

Hypotheses

- All the changes to the original architecture still preserve some invariants (wrt forwarding)
  - ‘Axioms’ of communication
- If we can state these axioms and analyze them, we can know the limits of what is feasible
  - eg. deliverability of messages
- We can also come up with an expressive pseudo-language to implement *any* packet forwarding scheme

Divide and Conquer

- We are only studying connectivity (naming, addressing, routing, forwarding)
- Other areas, such as medium access, reliability, flow control, congestion control, and security are ignored (for now)

A diversion...

Axiom: arch

Coliseum, Rome

Axiom: lintel

Big temple, Thanjavur, India

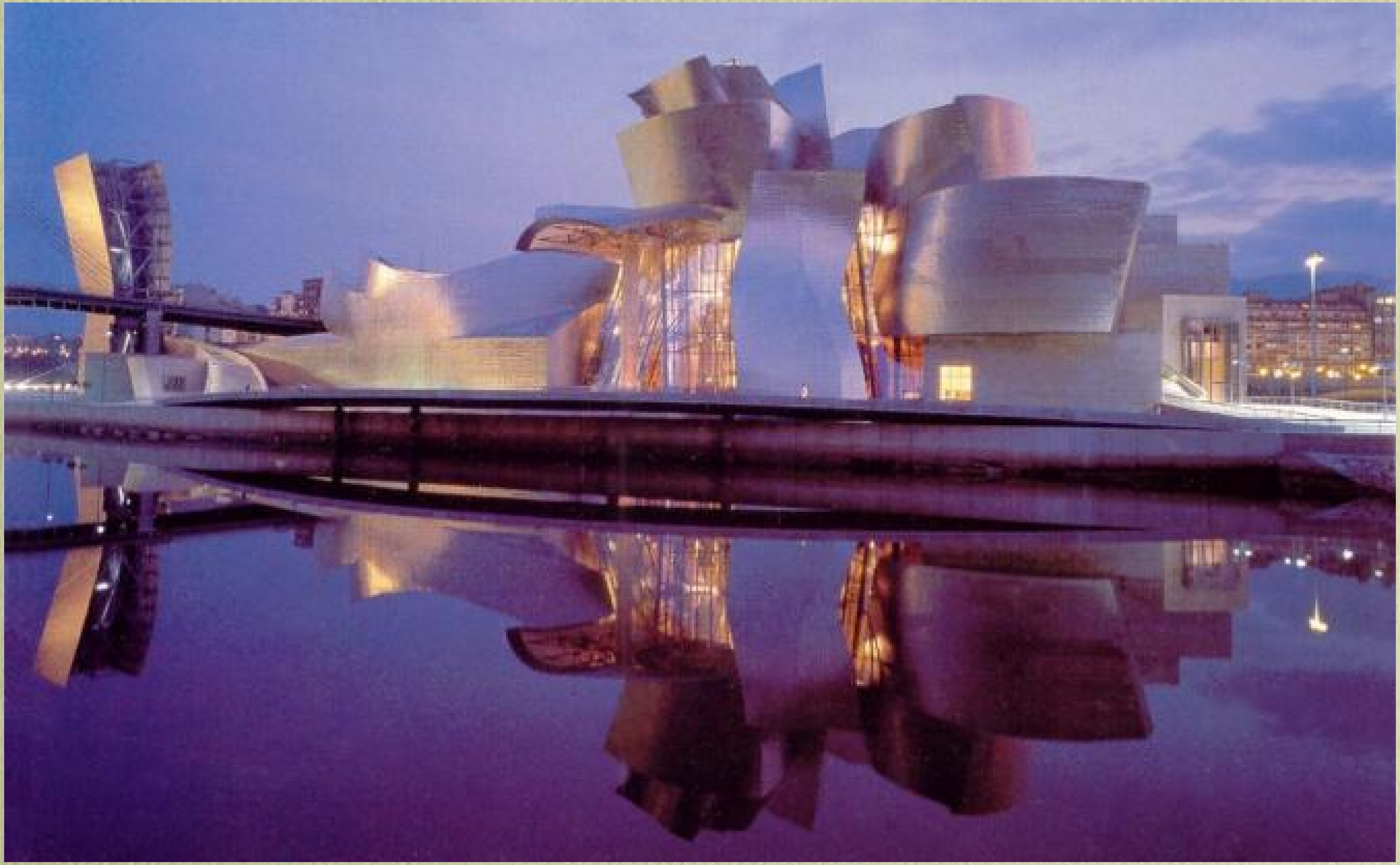
Internet-style architecture

Hearst Castle, California

Axiomatic engineering

Tenerife Airport, Tenerife,
(Calatrava)

Axiomatic engineering



Bilbao Museum (Gehry)

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The axioms

- Will state them, and try to explain why we chose them
- Grouped into a few sets

Naming and binding

Millau Viaduct

Naming and Binding

- Saltzer (1978) with some modifications
  - An *object* is a software or hardware structure
  - *Name* is a regular expression that refers to a set of objects
  - *Binding*
    - noun: mapping from name to set of objects
    - verb: choosing the object mapped to a name
  - *Address*
    - A lower-level name used to access an object

Naming and Binding...

- *Context*
  - Set of mappings
  - Name is interpreted wrt a context (multiple contexts may resolve the same name differently)
- *Resolution mechanism*
  - Locates the mapping for a name within a context

Communication axioms

MIlau Viaduct

Communication axioms

- Certain objects can *directly communicate* with each other
  - shared memory or on a physical medium
- *Network Processing Object* (NPO) is an object that can directly communicate with some other NPO(s)
- Each NPO has a local set of mappings, called its *context state* (e.g. forwarding table)

Communication axioms

- NPOs that can directly communicate with each other are *neighbours*
- Unit of communication is a *message*
  - message = header + payload
- ***Any name in a header is an address***
  - Header can have a *stack* of addresses
  - Topmost one is the current *destination* address

Communication axioms

- *Forwarding* is an extension of direct communication where neighbours repeatedly pass on a message to a set of neighbours, so that the message eventually arrives at a set of destination NPOs
  - transitive relation of direct communication
- *Resolution* can not only return a ‘lower-level’ name, but also set of neighbours for a name

Operations

Fundamental operations

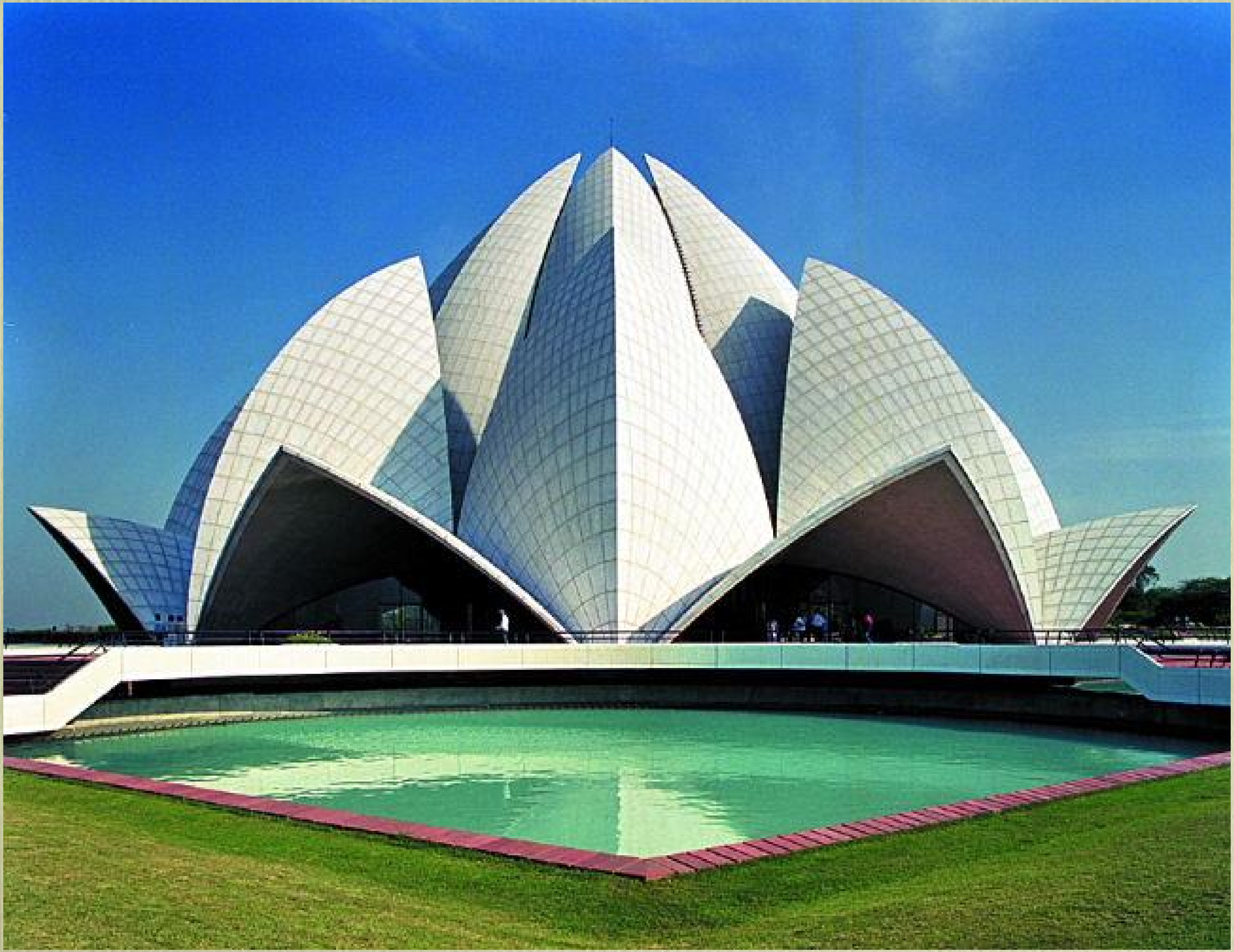
- Split operations into forwarding (move messages) and control (routing, path setup, remote name lookup)
- We describe some fundamental ways to move and manipulate a message, e.g.
  - receive/send – direct communication
  - push/pop – modify address stack
  - lookup (a name in a context table)

Forwarding

- Define local context state as
  - {<name → {<NPO, name>}>}
- Forwarding code:

```
message msg = receive();
name n = pop(msg);
{<NPO, name>} S = lookup(n);
for each <NPO, name> s in S
    outmsg = copy(msg);
    push(outmsg, s.name);
    send(s.NPO, outmsg);
endfor
```

Structural axioms



Baha'i Temple, New Delhi

Structure axioms

- The NPO that pushes an addresses and every NPO that resolves (i.e. lookup) or removes that address are *peers*
- Peers that push and pop an address establish a *link*
- Sequence of peers forming a link is a *path*

Structure axioms

- *Iterated forwarding* a message is binding its destination name to a set of destination NPOs
- Set of peer NPOs that forward a message with the same destination address to the same set of NPOs provide a *consistent binding*
- A *scope* of a name is the set of peers that provide a consistent binding for that name
- Scopes may contain special names, such as the *broadcast* name
- Mechanisms to provide consistency in a scope are called *routing*

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Formalization

- We associate operational semantics with each operation, consistent with axioms
- Desirable properties become theorems
  - e.g. we can ask “Is deliverable (A,B) a valid theorem in our system?”

Operational semantics

- Each operation updates the state of an abstract machine
- configuration =
  <stack of values | context state | operations>
- e.g.
  $<(n_1 n_2 n_3 \ldots n_d)|cs|pop;p'> \rightarrow <n_1,(n_2 n_3 \ldots n_d)|cs|p'>$
- Well-known theory to reason about invariants about partial correctness and progress

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Railway Station, Lisbon (Calatrava)

Sample Observations

- NAT ≈ MPLS ≈ ATM
  outgoing source port ~ label
- Recursive DNS lookup – forwarding based on DNS destination using UDP tunnels
- Stack of <port number, IP protocol ID, IP address, Eth protocol ID, MAC address>
  ≈ record route and source routing

Conclusions

- The Internet is complex, yet it works
- We think it’s because protocol designers implicitly follow some rules (axioms)
- We explicitly state the axioms – clarity
- Allows us (hopefully) to do formal analysis: correctness, deliverability, (performance, errors)
- Also allows us to construct a universal forwarding engine