Experiences with Modeling Network Topologies at Multiple Levels of Abstraction

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… *and a cast of hundreds*

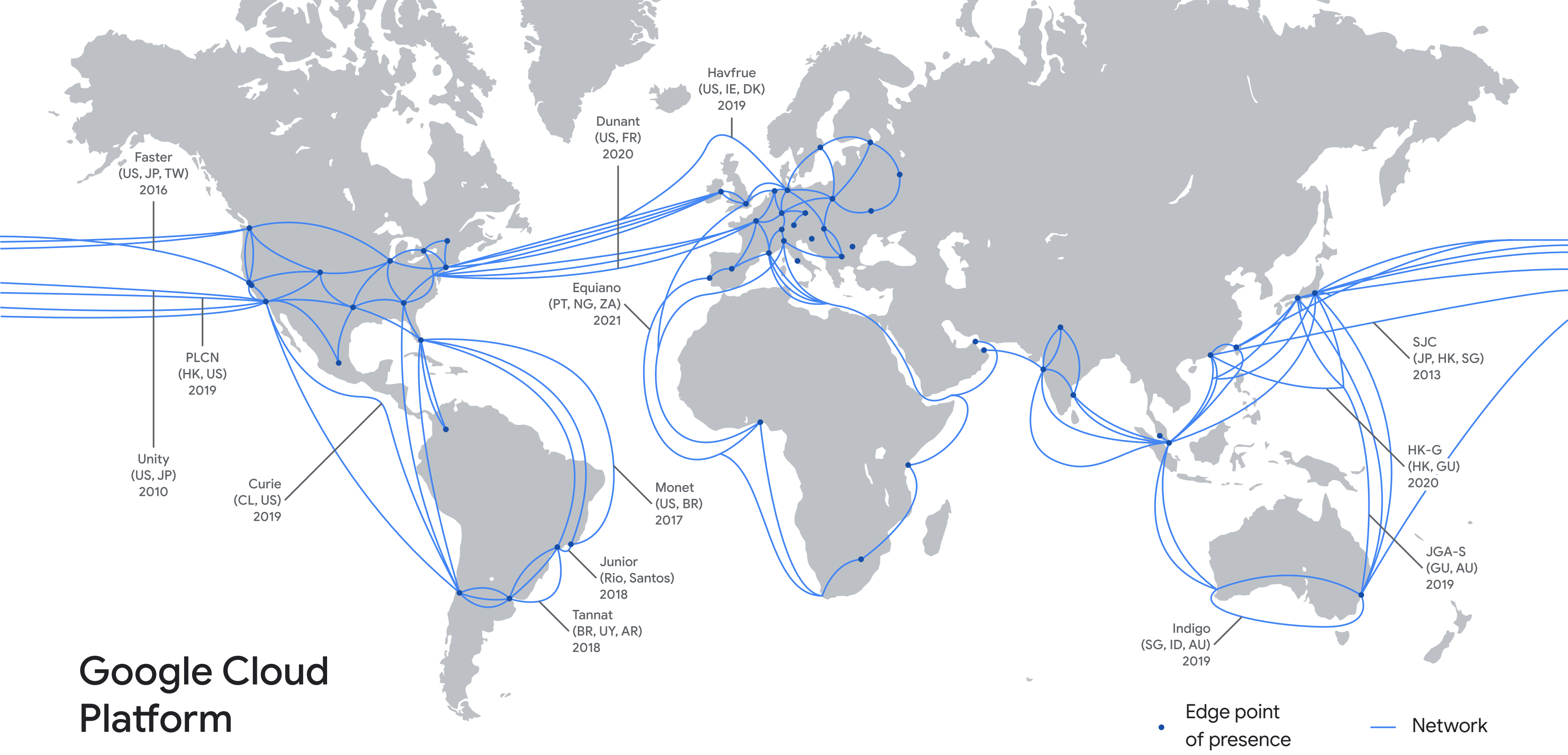
A common standard for representing network topology

It's not as easy as you might think -- the paper tries to explain what we learned

- This talk only scratches the surface

Google has some big networks

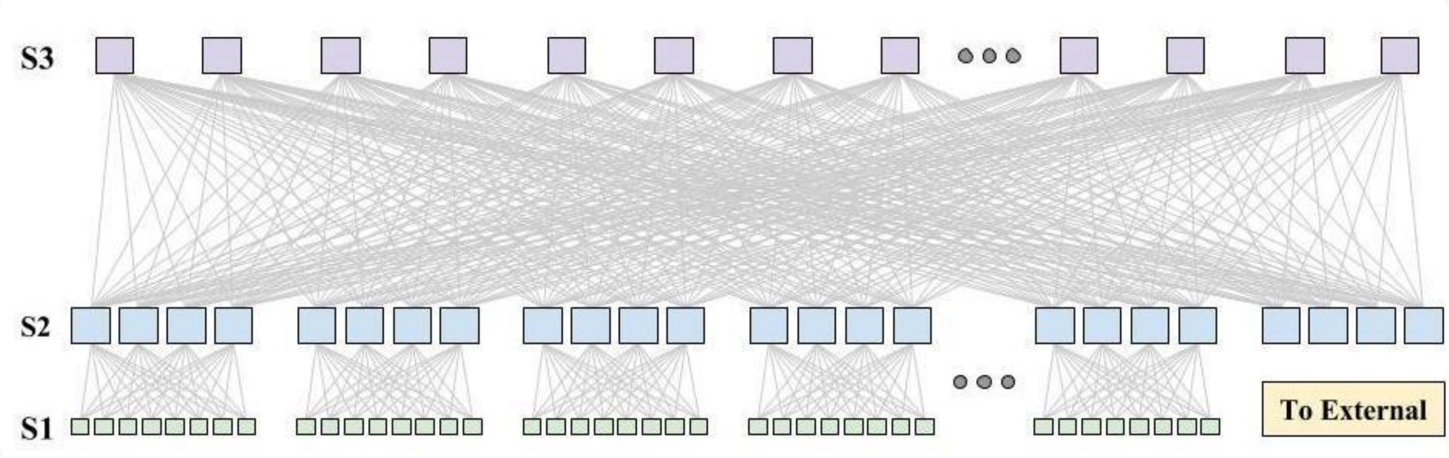
Google Cloud Platform



PoPs and network: 134 points of presence and 14 subsea cable investments around the globe (as of Feb 2020) (Google internal data)

Google | google.com/datacenters

These networks have a lot of wires ...



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Big networks need automated management

At our scale, we need to automate all phases of managing a network:

- Demand forecasting and capacity planning
- High-level network design
- Detailed network design
- Ordering materials -- racks, switches, cables, etc.
- Installing the physical network (instructions to human operators)
- Configuring switches and SDN controllers
- Monitoring the state of the network and its pieces
- Diagnosing problems

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Note: smaller networks need automation, too -- it's just less obvious

Automation needs data

In order to automate safely, we need **precise and accurate data** about our networks:

- High-level plans for connectivity
- Low-level details of connectivity
- Device & controller configuration
- Access control policies
- Routing policies
- IP address allocations

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} topology intent for a network

} derived from topology intent

} policy intent controlling how topology intent leads to config

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Topology: the starting point for almost all inputs to automated network management

A common standard for representing network topology

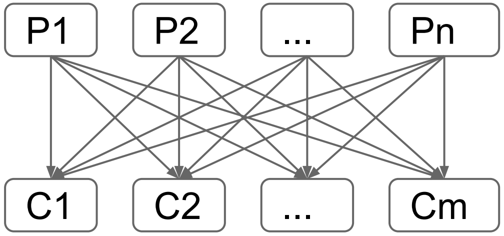
Multi-Abstraction-Layer Topology (MALT):

- Google's internal standard for (almost) all representations of network topology
- Supports interoperability between many software systems
- Supports multiple layers of abstraction
- Supports extensibility and evolution
- Supports declarative approaches to network management
- Supported by a rich software ecosystem

Why a standard representation?

Prior to adopting MALT, we had lots of *ad hoc* producer-consumer agreements

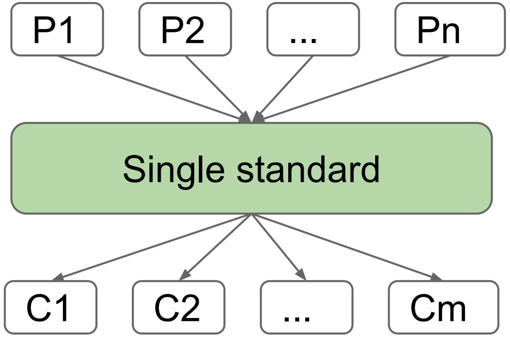
- knowledge was often hidden in code



*No standard: m*n agreements*

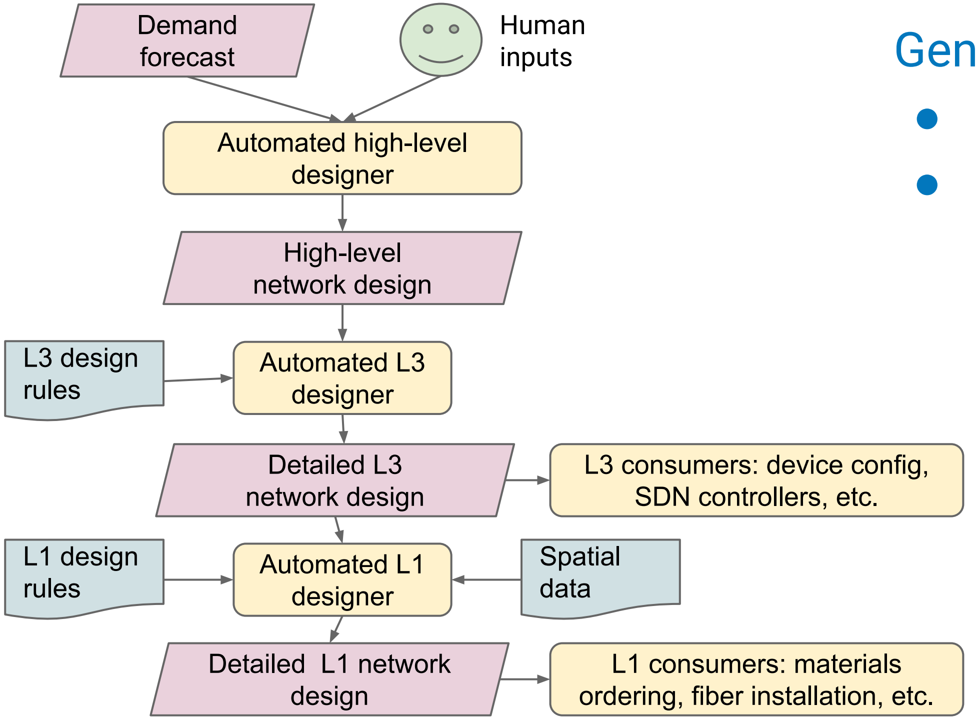
A standard representation:

- **decouples** producers and consumers
- **exposes knowledge** in the data, rather than hiding it in code
- enables the development of **shared infrastructure**
- Overall: enables faster innovation



With standard: m+n agreements

Example: MALT for a multi-phase network design pipeline



Demand forecast

Human inputs

Automated high-level designer

High-level network design

L3 design rules

Automated L3 designer

Detailed L3 network design

L3 consumers: device config, SDN controllers, etc.

L1 design rules

Automated L1 designer

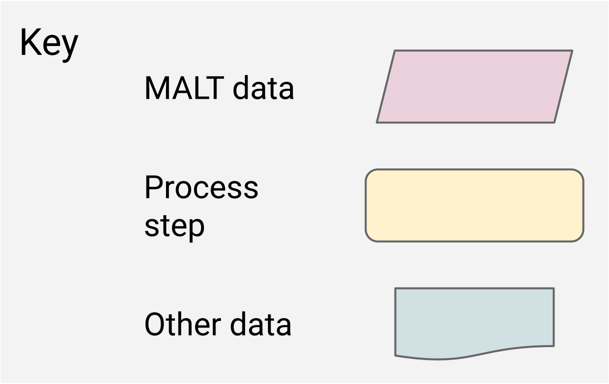
Spatial data

Detailed L1 network design

L1 consumers: materials ordering, fiber installation, etc.

Generate network designs automatically

- Start with high-level abstractions
- Expand detail at each step, based on additional data



Key

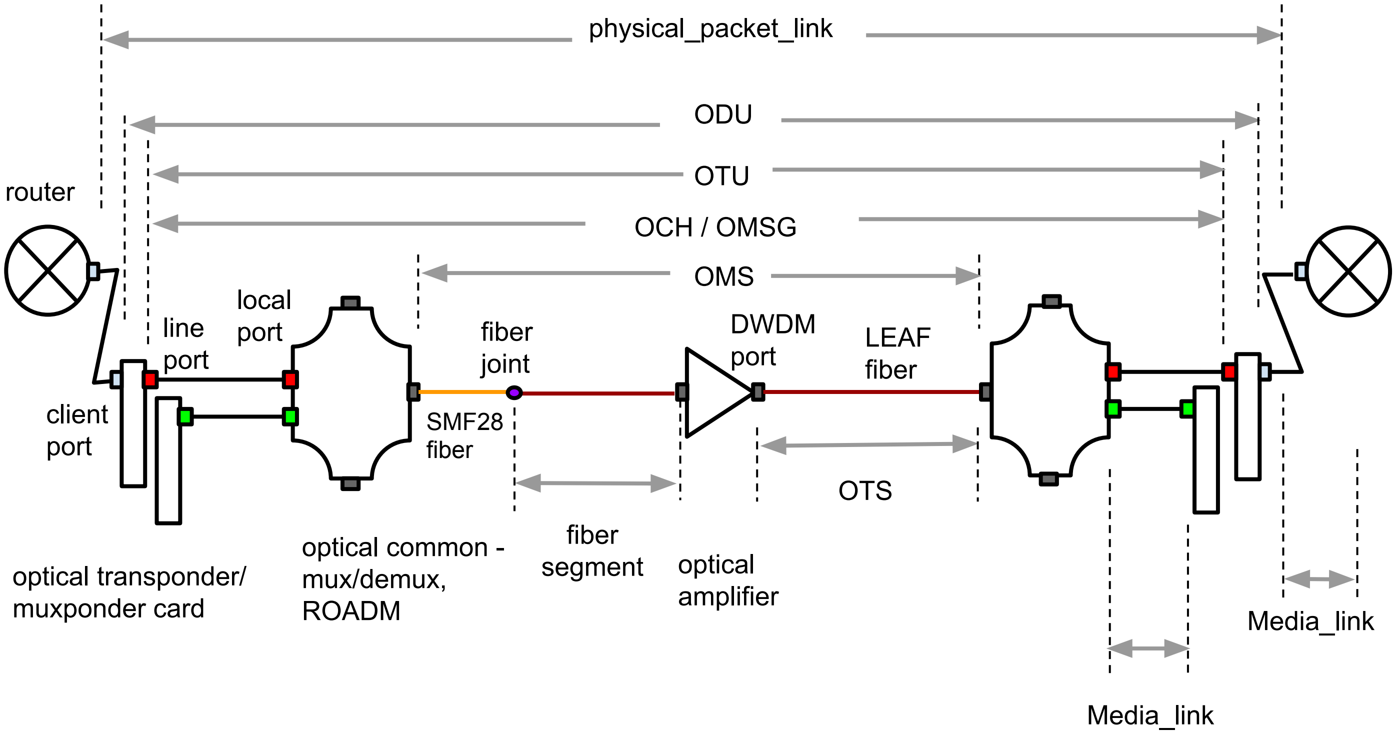
MALT data

Process step

Other data

Abstractions go deep

Example of "Optical Transport Network" hierarchy (used in WANs)



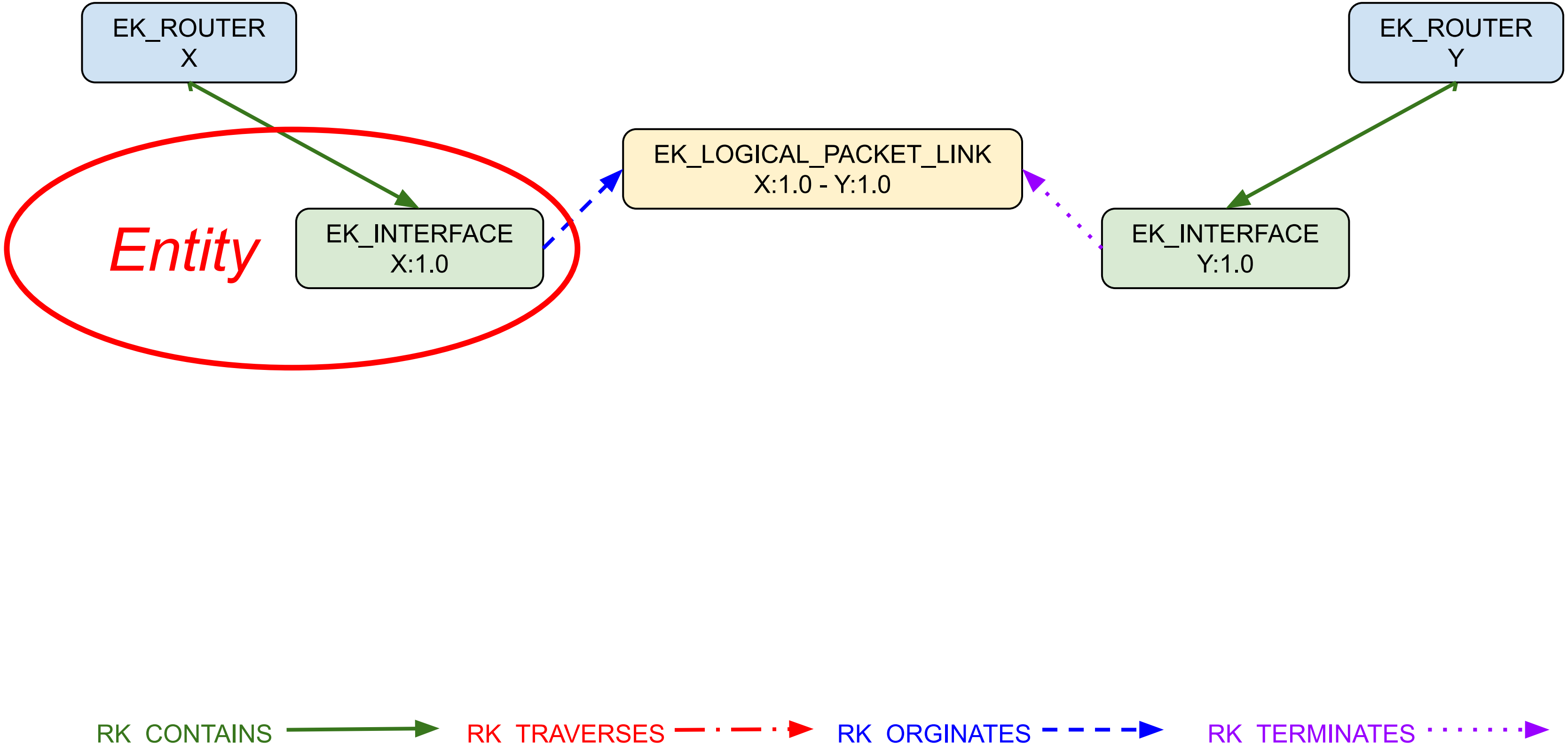
Basics of MALT

- MALT is an *entity-relationship model*:
  - *Entities* represent things: real or abstract
  - Entities have *entity-kinds*, *names* and *attributes*
  - *Relationships* connect entities, and don't have attributes
- Example real entities: routers; connectors; fibers; server machines; racks
- Example abstract entities: Clos networks; trunk links; groups of all sorts
- Example relationships: contains, aggregates, controls

MALT today has:

- ca. 250 entity-kinds
- ca. 20 relationship-kinds

Trivial entity-relationship graph (one L3 link)



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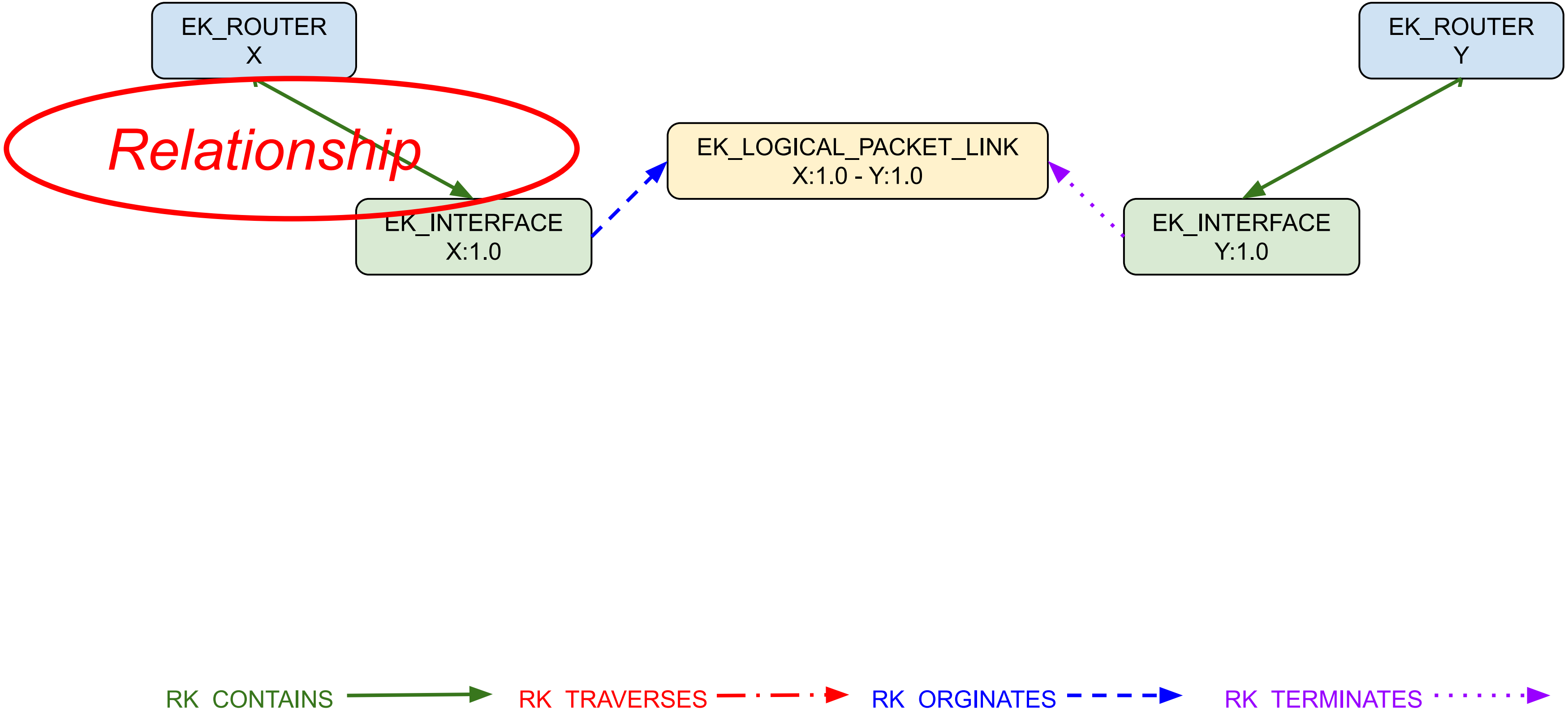

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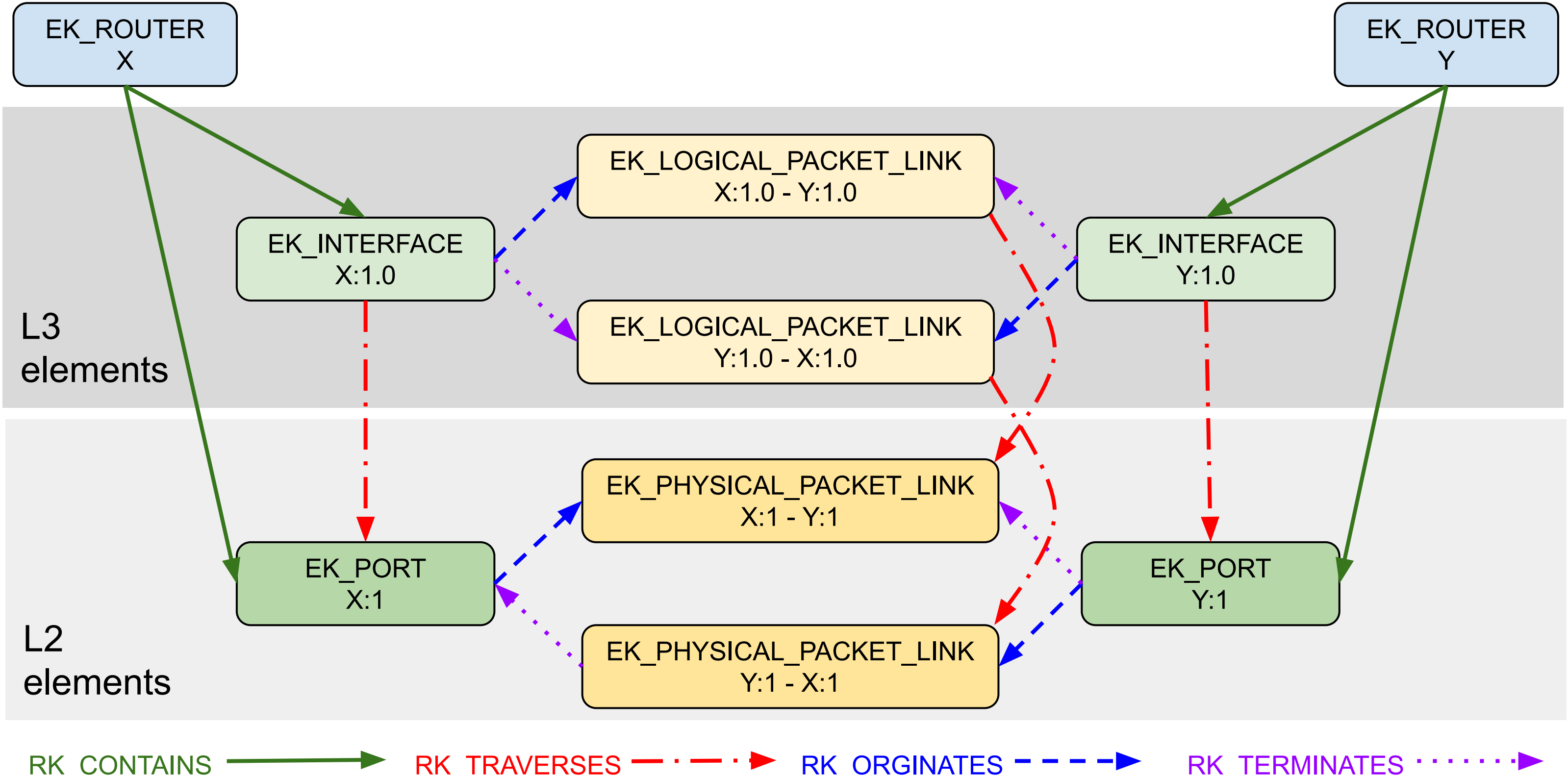

"This looks too verbose"

MALT is meant for computers, not for humans!

- Computers are good at processing graphs with millions of entities
- Software is bad at making inferences -- it's better to have too much detail

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But we can still express MALT graphs in text, when we have to:

```
EK_ROUTER/X RK_CONTAINS EK_INTERFACE/X:1.0
EK_INTERFACE/X:1.0 RK_TRAVERSES EK_PORT/X:1

EK_ROUTER/Y RK_CONTAINS EK_INTERFACE/Y:1.0
EK_INTERFACE/Y:1.0 RK_TRAVERSES EK_PORT/Y:1

EK_LOGICAL_PACKET_LINK/"X:1.0 - Y:1.0"
  RK_TRAVERSES EK_PHYSICAL_PACKET_LINK/"X:1 - Y:1"
```

```
EK_PORT/X:1 RK_ORIGINATES
  EK_PHYSICAL_PACKET_LINK/"X:1 - Y:1"
EK_PORT/Y:1 RK_TERMINATES
  EK_PHYSICAL_PACKET_LINK/"X:1 - Y:1"

EK_INTERFACE/X:1.0 RK_ORIGINATES
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EK_INTERFACE/Y:1.0 RK_TERMINATES
  EK_LOGIICAL_PACKET_LINK/"X:1.0 - Y:1.0"
```

(this is about 80% of the previous diagram)

Entity attributes

Attributes allow us to express intent and status for specific points in the topology

Partial examples for EK_PORT and EK_INTERFACE, using Google *Protocol Buffer* notation:

```
port_attr: <
  device_port_name: "port-1/24"
  openflow: <
    of_port_number: 24
  >
  port_role: PR_SINGLETON
  port_attributes: <
    physical_capacity_bps: 40000000000
  >
  dropped_packets_per_second: 3
>
```

```
interface_attr: <
  address: <
    ipv4: <
      address: "10.1.2.3"
      prefixlen: 32
    >
    ipv6: <
      address: "1111:2222:3333:4444::"
      prefixlen: 64
    >
  >
>
```

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```

intent attributes

observed attribute

MALT's software ecosystem

MALT's representation would be useless without a rich software ecosystem:

- Libraries to support common operations and hide some details
- Systems to automatically generate detailed models from abstract models
- Model visualization and network visualization GUIs
- A domain-specific query language
- A scalable, reliable storage system

MALT queries

Most applications navigate small regions of a model, not an entire graph

- e.g.: generate config for a single device; figure out what fails if a rack dies

MALT has a **query language** to make this reasonably efficient

- It's hard to get the right tradeoff between expressive power and usability
- The raw query language is still confusing to many programmers
    - We added a layer of "canned queries" with specific semantics
        - E.g. "All L2 links between a pair of switches" or "Rack that contains a line card"
    - Canned queries also insulate clients against many kinds of schema change

- Why didn't we use SQL queries?
    - We have good reasons not to expose SQL … see the paper

Example MALT query

```
# Given a device, find its geographical information and
# the ports and interfaces it contains.
cmd { find { match { id { kind: EK_DEVICE name: 'foo' }}}}
cmd
  branch {
    # Expand backwards.
    sequence {
      cmd {
        follow_until {
          kind: RK_CONTAINS dir:DIR_BACKWARDS
          target { match { id { kind: EK_CONTINENT }}}
        }
      }
    }
    # Expand forwards.
    sequence {
      cmd {
        follow_until {
          kind: RK_CONTAINS
          target {
            match { id { kind: EK_PORT } }
          match { id { kind: EK_INTERFACE } }
          }
        }
      }
    }
  }
}
```

Storage: MALTshop

We wanted a single (replicated) service for storing MALT models:

- Implement and operate just one high-availability service, not lots of them
- Promote controlled sharing between applications and teams
- Ensure there's an easy way to find anything across all of our network models

MALTshop:

- Supports zillions of named "shards" with ACLs + immutable-version semantics
- Efficient support for incremental updates, queries, etc.
- Based on Spanner for scale and geo-consistency
- Currently: thousands of shards, millions of entities/shard, 1000s of queries/sec

This is not as easy as you might think

We learned a lot of lessons, the hard way

- Schema design principles (and the need to be rigorous about them)
- Support for schema evolution
- Structure design pipelines as dataflow graphs, not shared-database updates
- Use different models for different phases of a network's lifecycle
- Migrating users from older representations (it's really hard)
- The dangers of string-parsing (it's really bad)
- Using human-readable names for entities (not our best idea)
- A good representation doesn't save you from dirty data

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Only enough time for a few of these topics; see the paper for the others

Schema design principles

- "Fewer entity-kinds" does not make the schema "simpler"
  - Overloaded concepts lead to ambiguity, which leads to complex/fragile code
- Instead, favor orthogonality and separation of aspects
  - Orthogonality: two "things" with mostly-disjoint attributes/relationships should be two EKs
  - Separation of aspects: complex things (e.g., routers) can be multiple EK (data plane, metal, etc.)
- Use explicit relationships rather than name-based attributes
- Use relationship-kinds consistently
  - Otherwise, it's harder to create straightforward queries

Schema evolution

Networks are complex and we're constantly innovating in unexpected ways

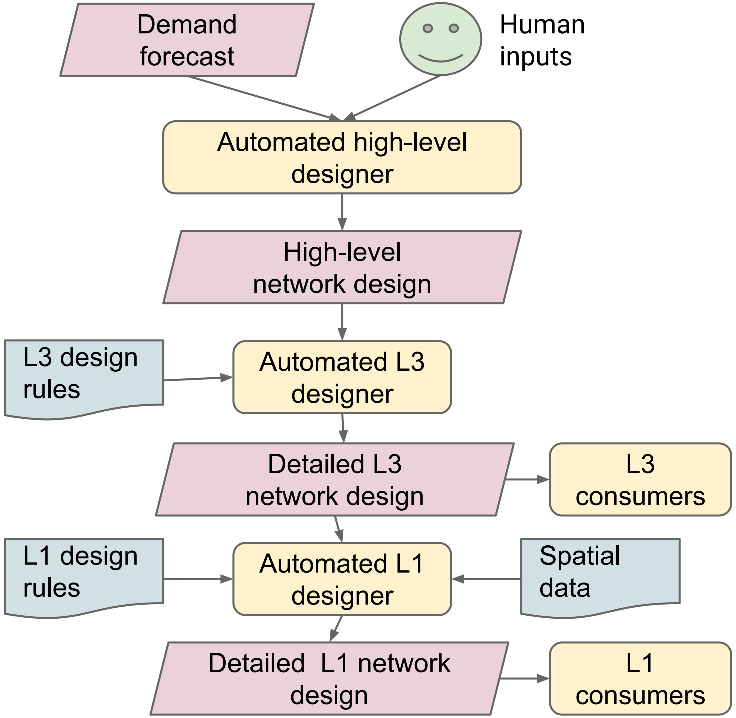
- So, the MALT schema needs to continually evolve

We use multiple processes to manage evolution:

- Curation of schema changes via expert "review board" + a written *Style Guide*
- "Profiles" to further constrain schema for specific parts of our networks
    - + machine-checkable profile language to enforce contract between producers + consumers
- Explicit profile versions, so consumers can evolve independent of producers
    - Automated model generation allows producers to create the same data for multiple profiles
- "Canned queries" insulate most consumers from much of our evolution

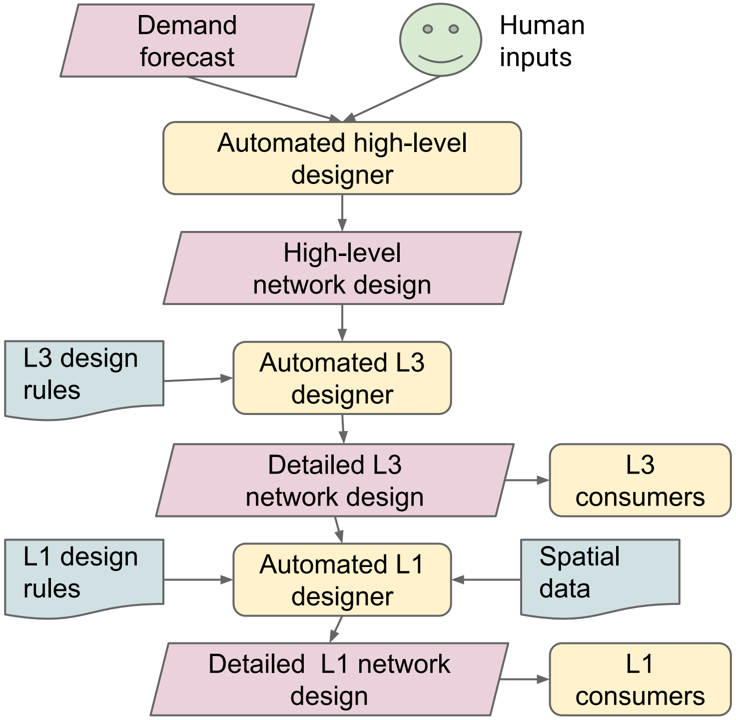
Abstraction is vital, but taxonomy is hard -- even for experts

Why we prefer dataflow design pipelines to databases



Dataflow-style design pipeline

Why we prefer dataflow design pipelines to databases



Dataflow-style design pipeline

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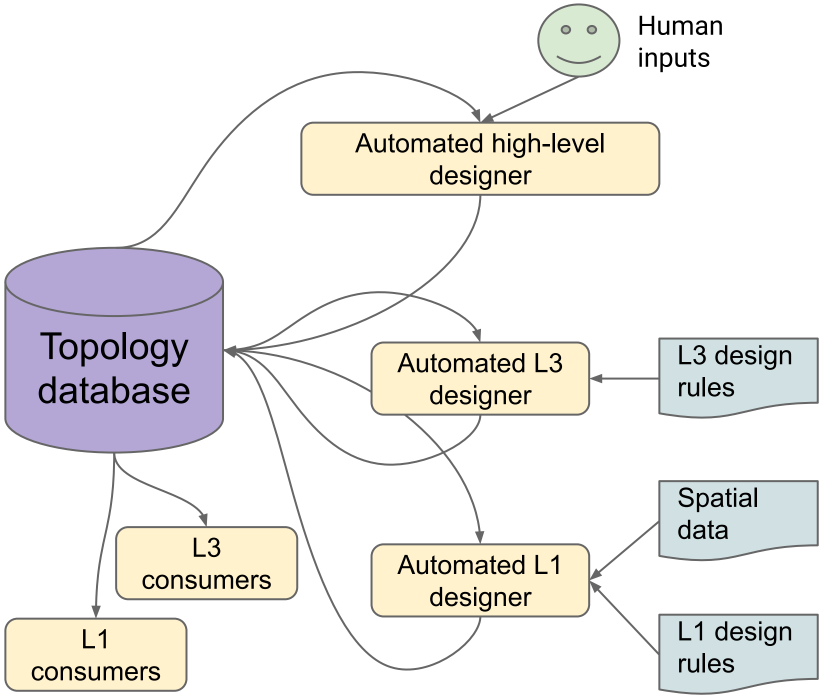
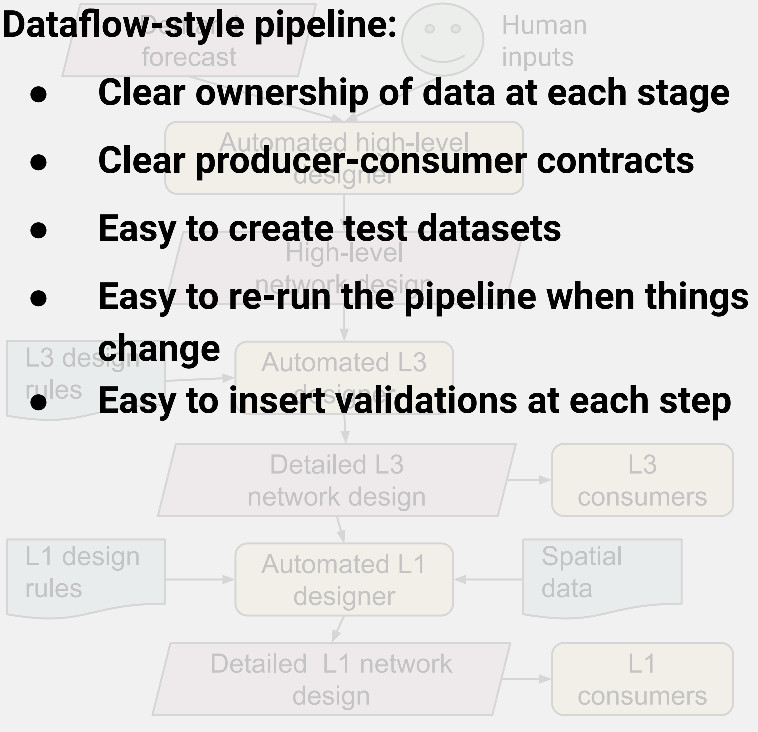


Database-style design pipeline

Why we prefer dataflow design pipelines to databases

Dataflow-style pipeline:

- **Clear ownership of data at each stage**
- **Clear producer-consumer contracts**
- **Easy to create test datasets**
- **Easy to re-run the pipeline when things change**
- **Easy to insert validations at each step**



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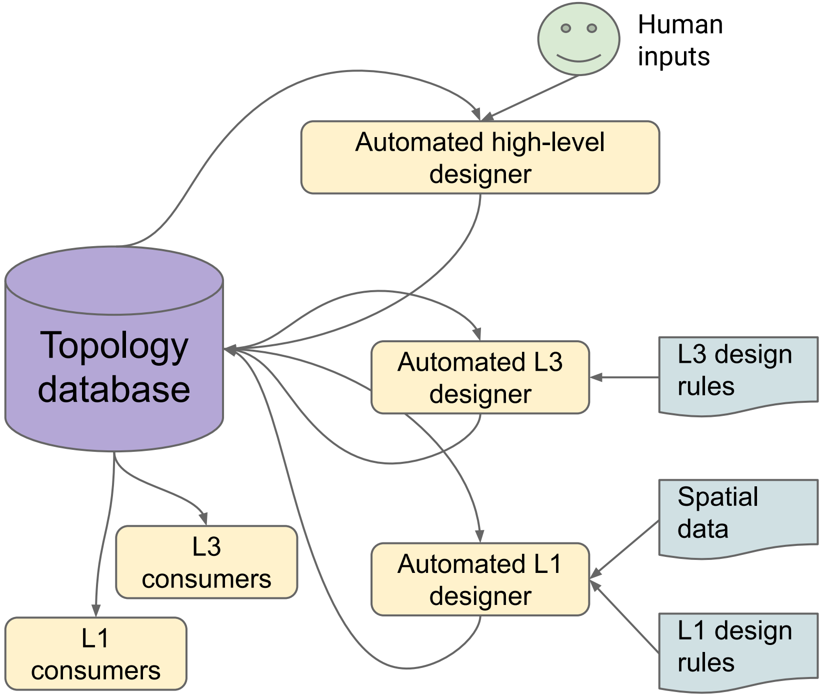

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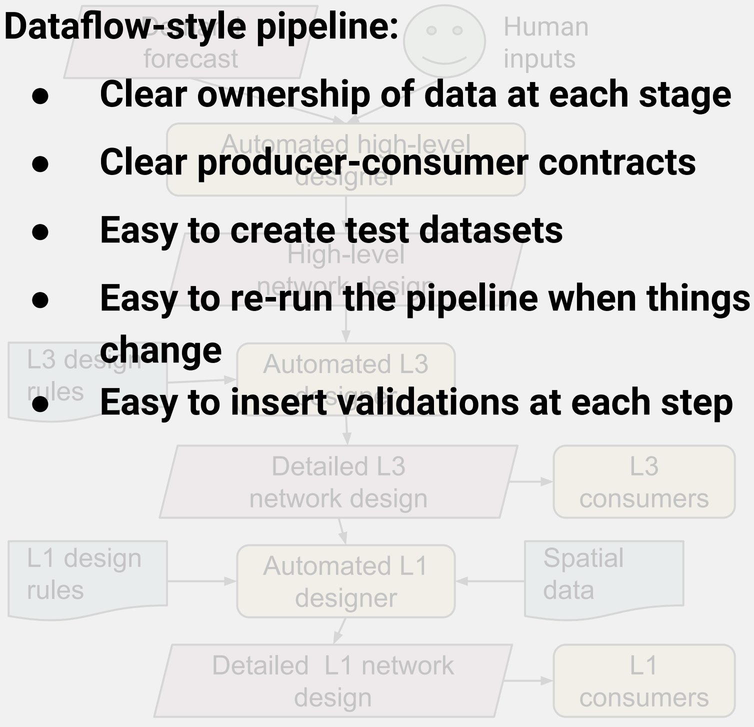
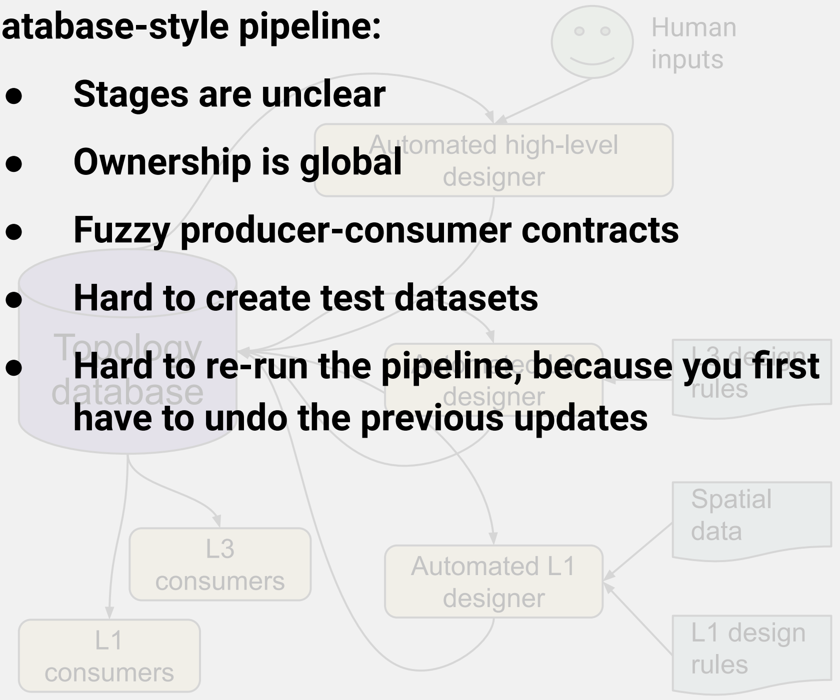


Dataflow-style design pipeline

Database-style pipeline:

- Stages are unclear
- Ownership is global
- Fuzzy producer-consumer contracts
- Hard to create test datasets
- Hard to re-run the pipeline, because you first have to undo the previous updates



Database-style design pipeline

Thanks!

- Automation requires both low-level detail and abstraction
- Abstraction is hard and requires support for controlled evolution
- A data-exchange format needs a full software ecosystem
- Network topology ties together all of our network management automation
- Network management: it's about the whole lifecycle, not just the running network