Experiences with multi-layer network modeling

Anees Shaikh, Google Global Networking
on behalf of many, many contributors

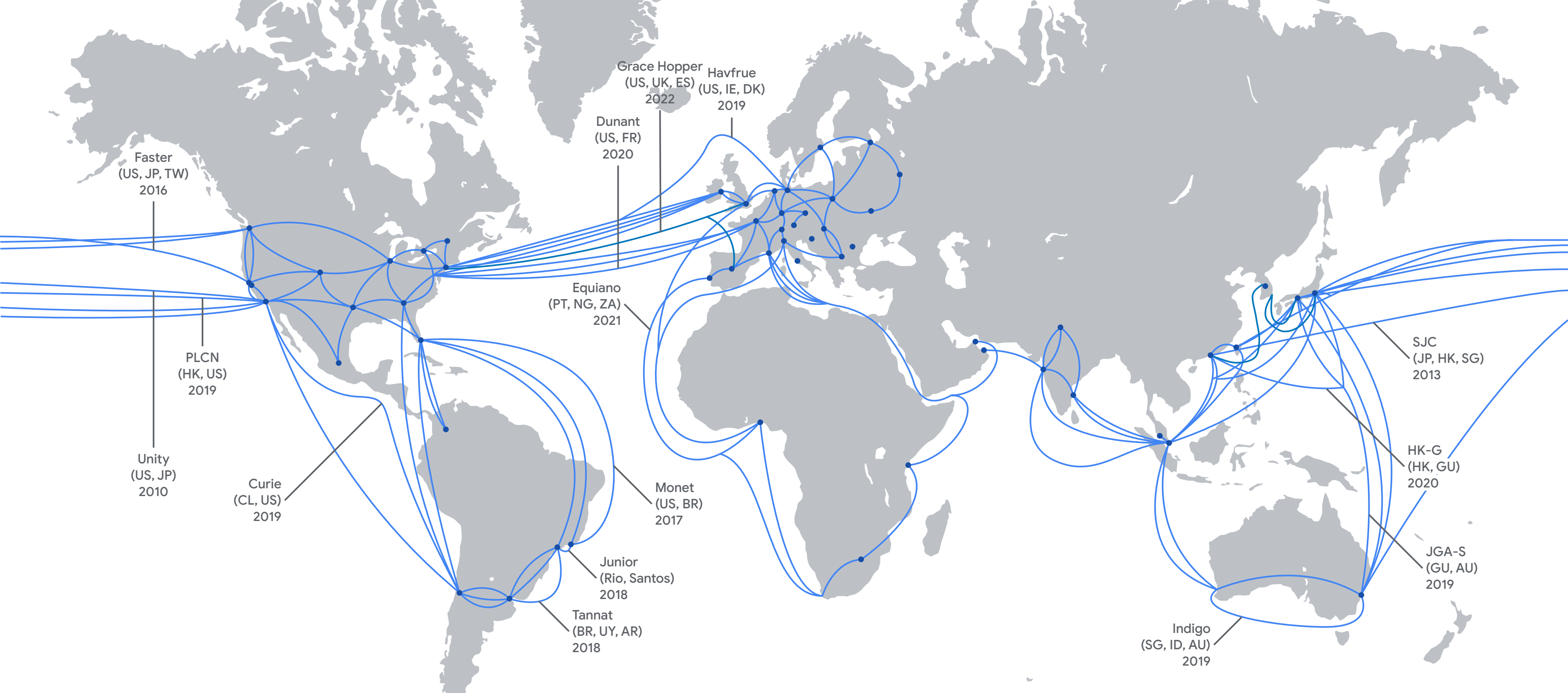
For more details: "Experiences with Modeling Network Topologies at Multiple Levels of Abstraction," Jeffrey C. Mogul, Drago Goricanec, Martin Pool, Anees Shaikh, Douglas Turk, Bikash Koley, Xiaoxue Zhao, *USENIX Symposium on Networked Systems Design and Implementation (NSDI 2020)*

A common standard for representing network structure

Motivation

Design choices

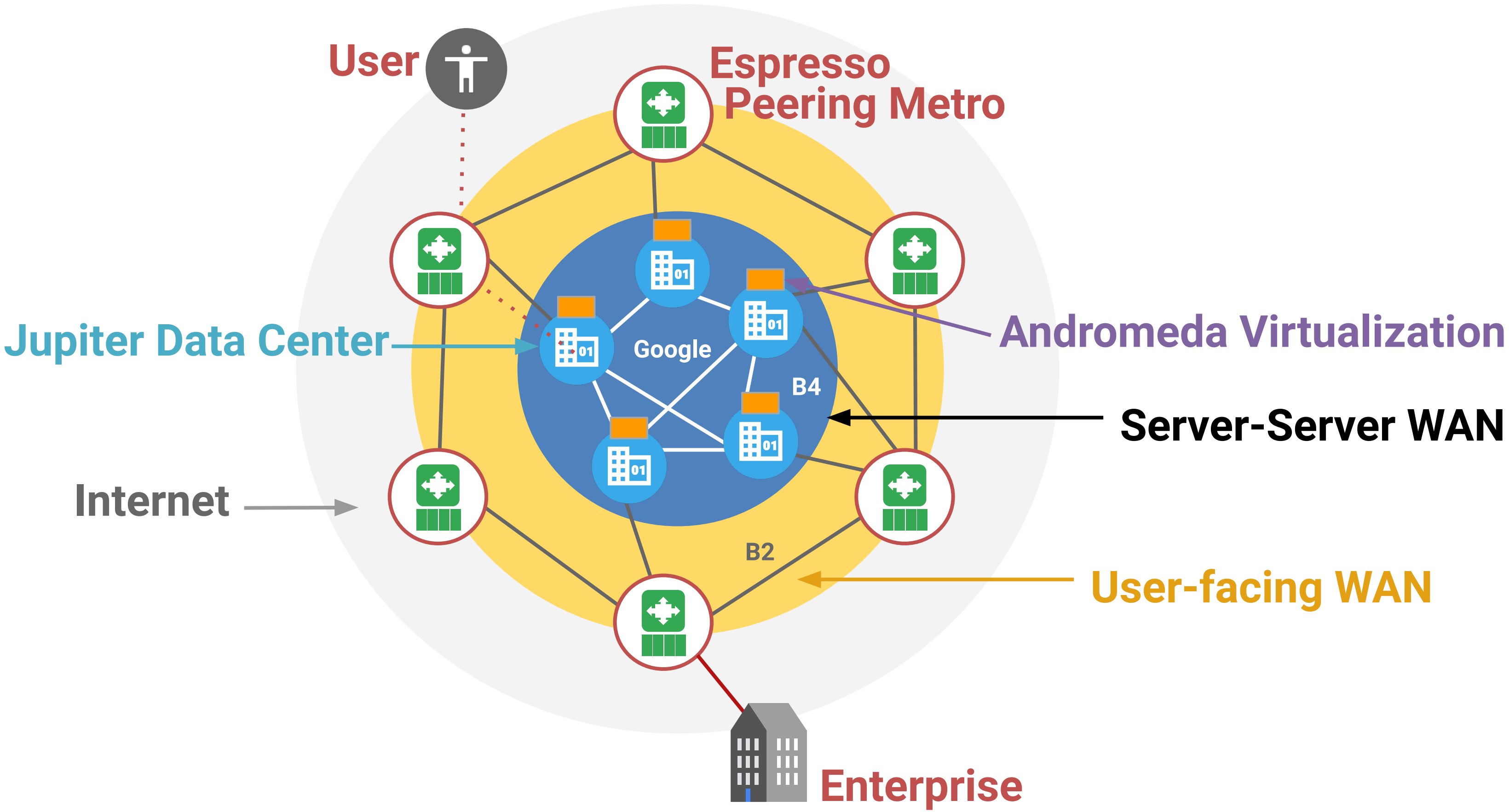
Lessons / experience that others may find useful



External view of Google Cloud Network

134 points of presence and 14 subsea cable investments around the globe

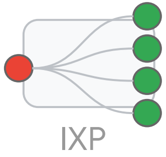
Google production networks



Automation is a requirement for all networks

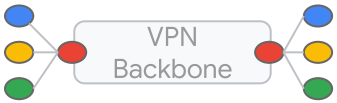
Scale

do more with the resources that we have



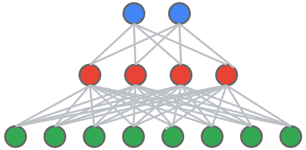
Consistency

consistent deployments, not snowflakes



Correctness

eliminate human inconsistencies



Common automation targets: device and link provisioning, configuration changes, monitoring / probing, troubleshooting ...

For large-scale networks, we need to automate all aspects of management:

- demand forecasting and capacity planning
- high-level network design
- detailed network design
- ordering materials -- racks, switches, cables, etc.
- installing the physical network (for human operators)
- configuring devices and controllers
- monitoring the state of all components of the network
- diagnosing problems

Automation needs data

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

Examples

- high-level plans for connectivity (future)
- low-level details of connectivity (soon / current)
- device and controller configuration
- access control policies
- routing policies
- IP address assignments

A common standard for representing network topology

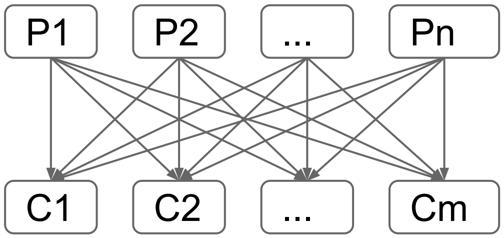
Multi-Abstraction-Layer Topology (MALT):

- Google's internal standard for (almost) all representations of network topology / structure
- provides interoperability between many software systems
- multiple layers of abstraction
- extensibility and evolution
- used to implement declarative network management systems
- supported by a extensive software ecosystem

Why a standard representation?

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

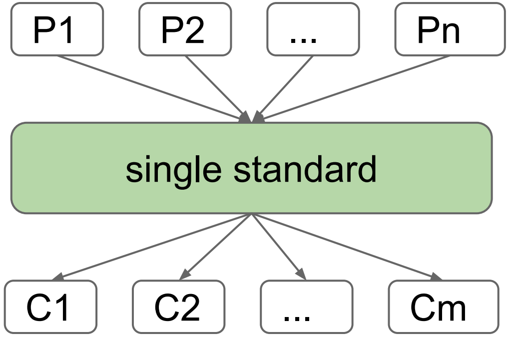
- knowledge was often hidden in code



*No standard: m*n agreements*

A standard representation:

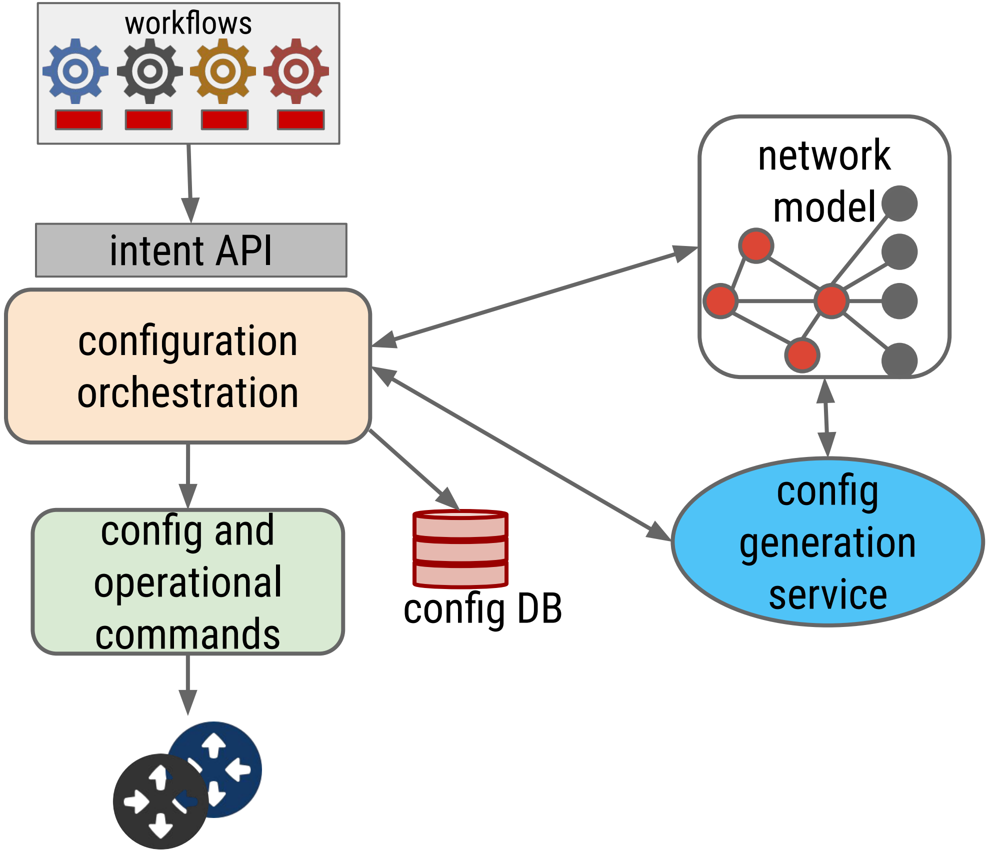
- **decouples** producers and consumers
- **exposes knowledge** in the data, rather than hiding it in code
- enables the development of **shared infrastructure**



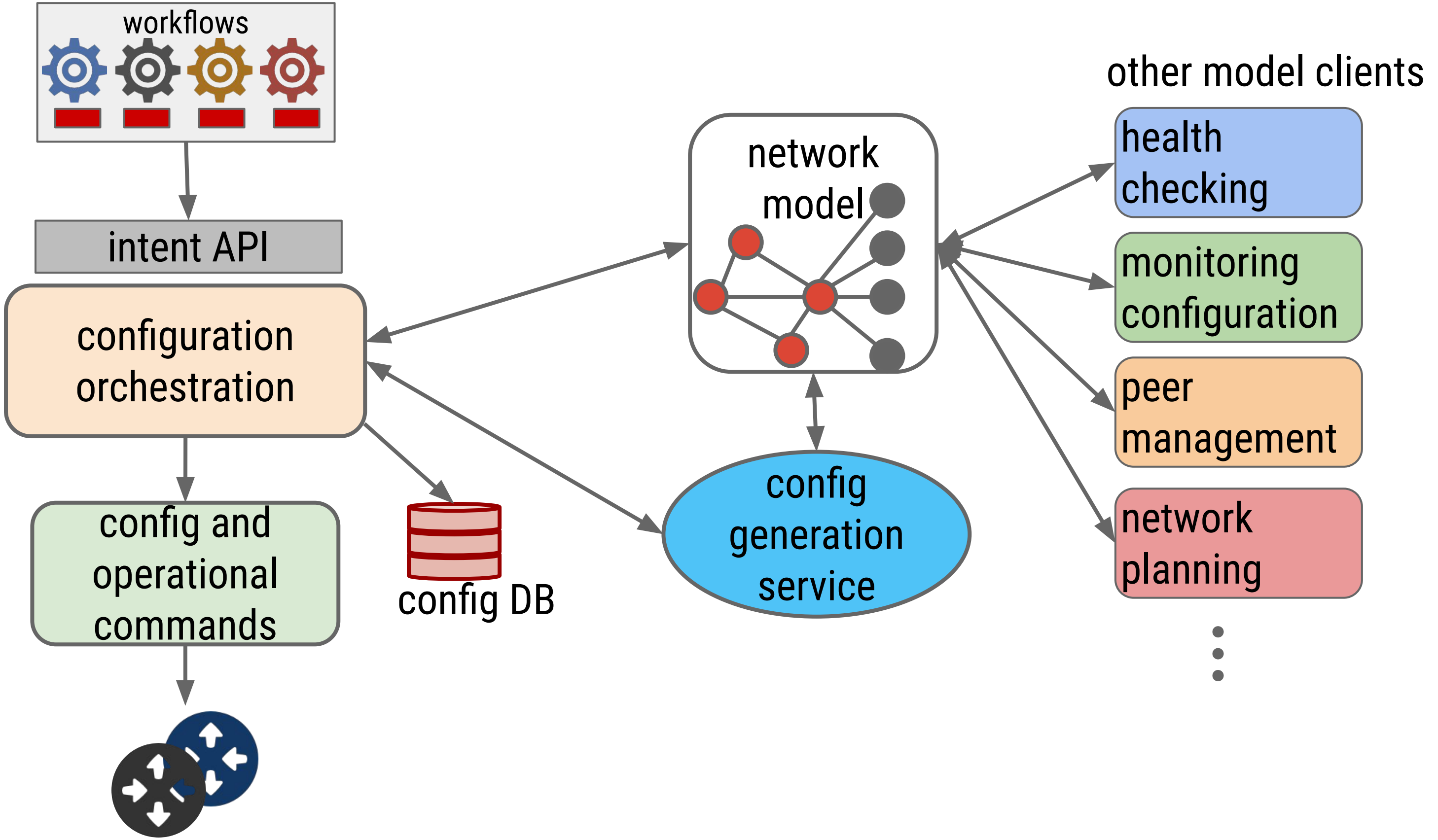
With standard: m+n agreements

Google

Example -- intent-driven configuration of the WAN



Example -- intent-driven configuration of the WAN



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

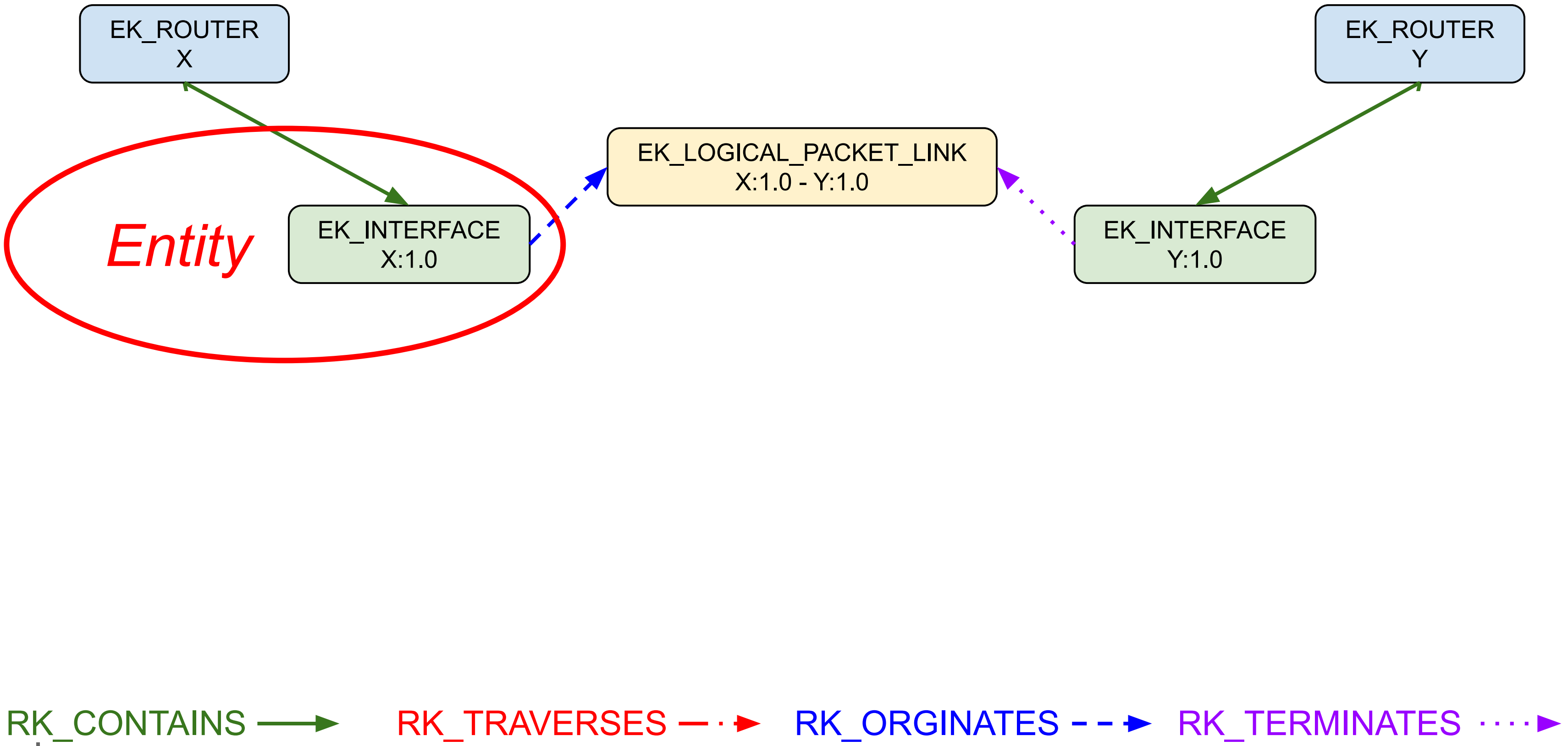
Examples

- real entities: routers, connectors, fibers, server machines, racks, buildings
- example abstract entities: Clos networks, tunnel / trunk links, groupings of all sorts
- example relationships: contains, aggregates, controls, configured_on

MALT today has:

- >250 entity-kinds
- ~20 relationship-kinds

Trivial entity-relationship graph (one L3 link)



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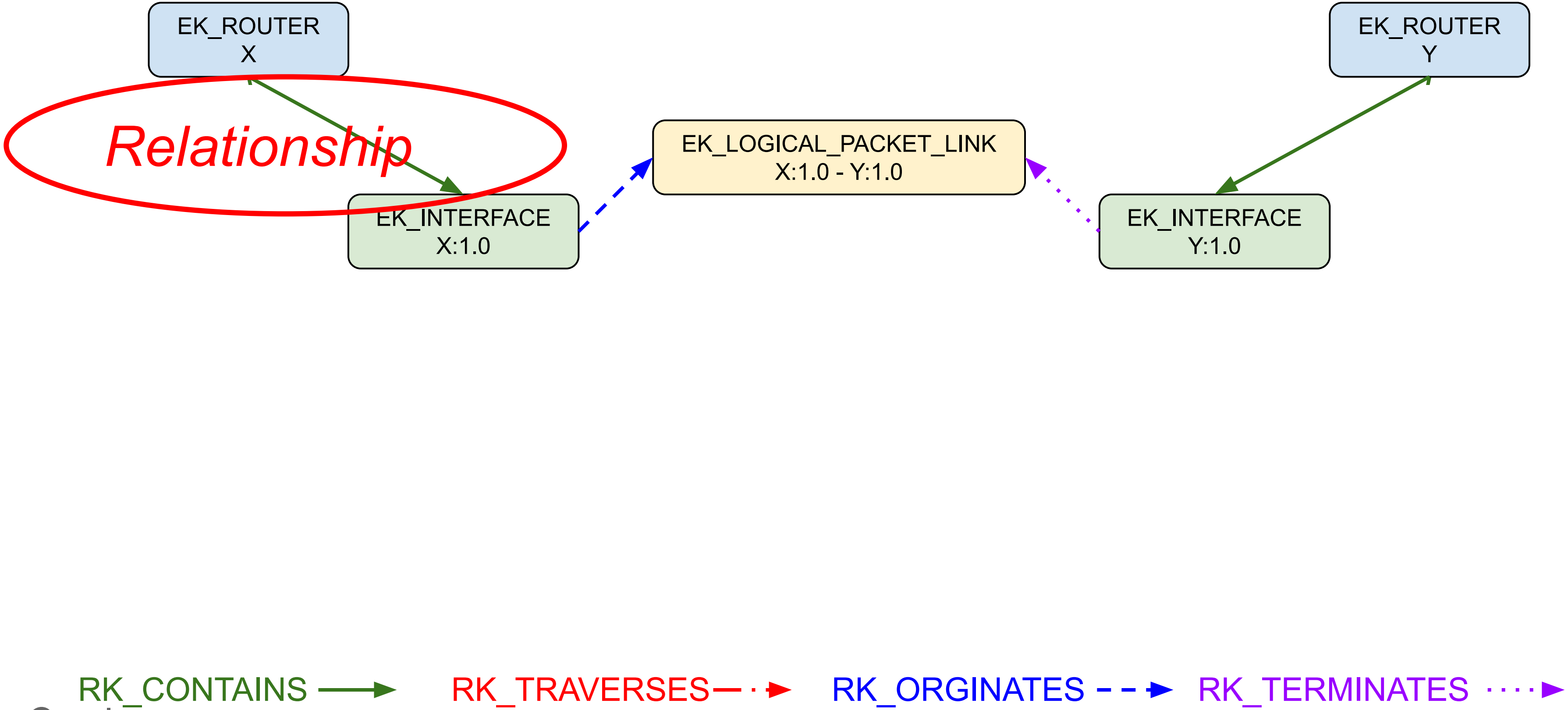

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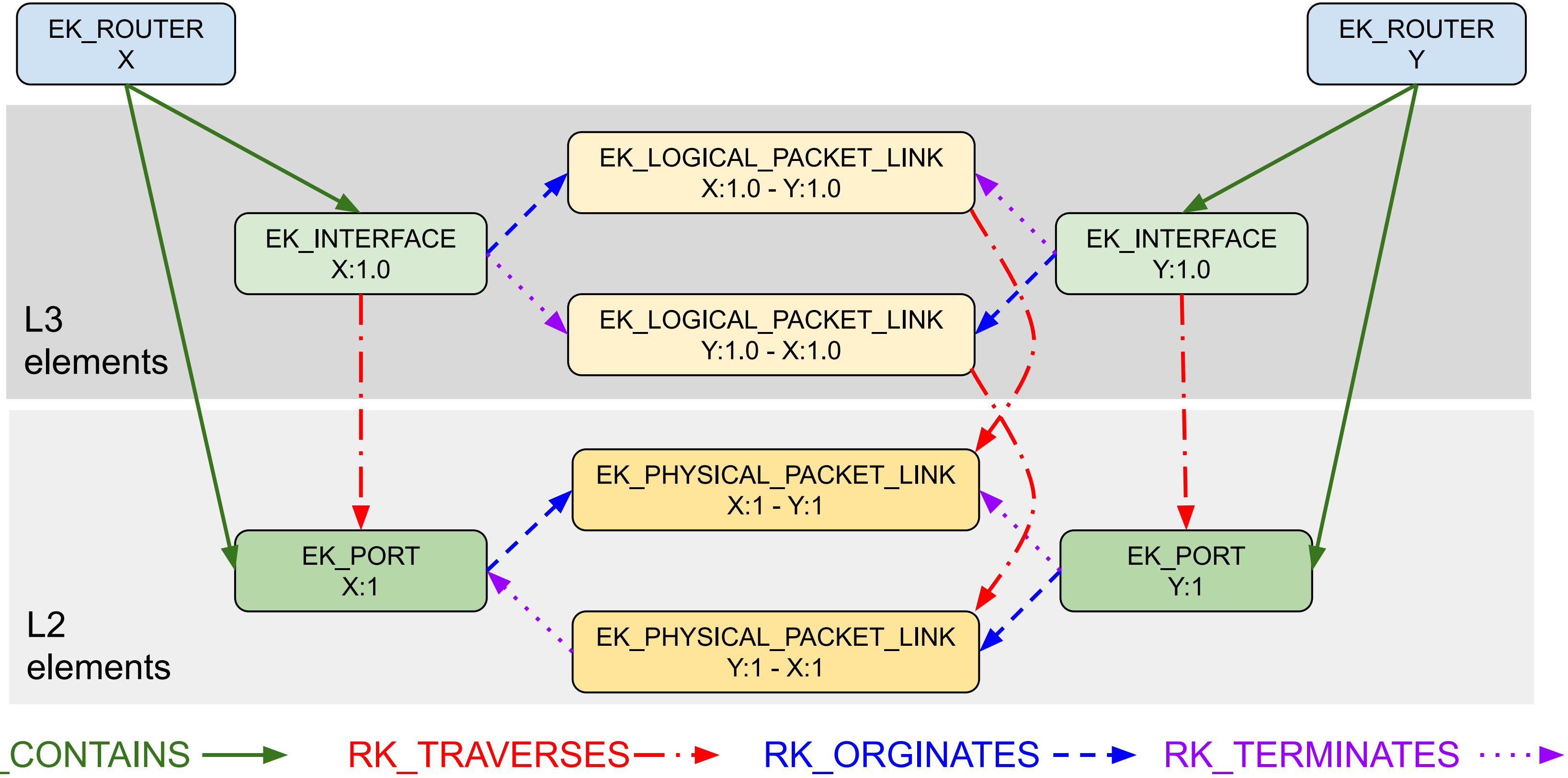


"This looks too verbose"

MALT is meant for computers, not for humans!

- computers are good at processing graphs with millions of entities
- software is bad at making inferences -- better to be explicit and have too much detail

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"
```

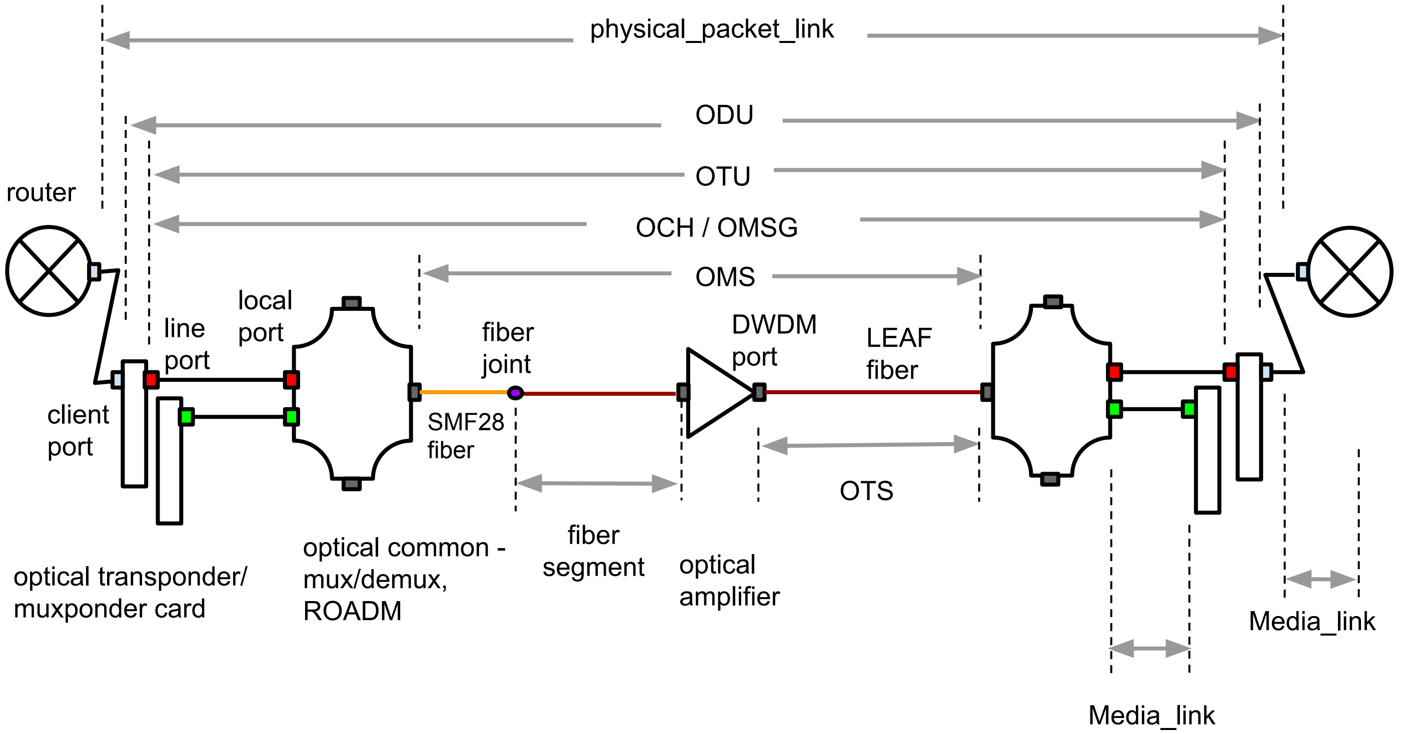
```
EK_PORT/X:1 RK_ORIGINATES
  EK_PHYSICAL_PACKET_LINK/"X:1 - Y:1"
EK_PORT/Y:1 RK_TERMINATES
  EK_PHYSICAL_PACKET_LINK/"X:1 - Y:1"

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

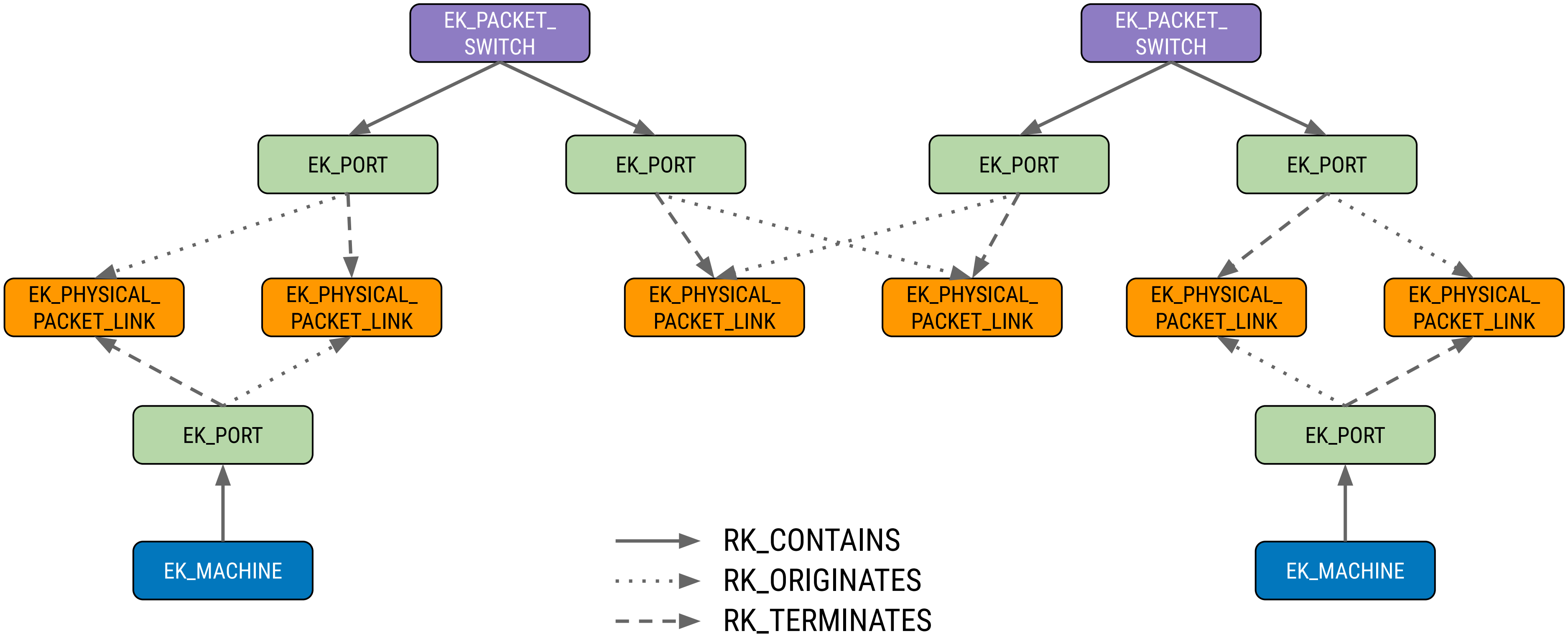
(this is about 80% of the previous diagram)

Abstractions go deep

Example: Optical Transport Network hierarchy (used in WANs)



Modeling a simple switched network topology



Entity attributes

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

partial examples for EK_PORT and EK_INTERFACE (protobuf 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
    >
  >
>
```

Google

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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
- autogenerated schema documentation
- model visualization and network visualization UIs
- 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

- challenging tradeoff between expressive power and usability
- raw query language is still confusing to many programmers
  - 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 changes

Why didn't we use SQL queries?

- reduce client coupling to the underlying SQL schema (more details in paper)

Storage: MALTshop

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 many, many 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

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 (avoid!)
- using human-readable names for entities (not our best idea)
- a good representation doesn't save you from dirty data

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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, chassis, etc.)
- bias toward explicit relationships rather than name-based attributes
  - there are some interesting trade-offs, however
- use relationship-kinds consistently
  - otherwise, it's harder to create straightforward queries

Schema evolution

networks are complex and we're constantly adding new modeling use cases

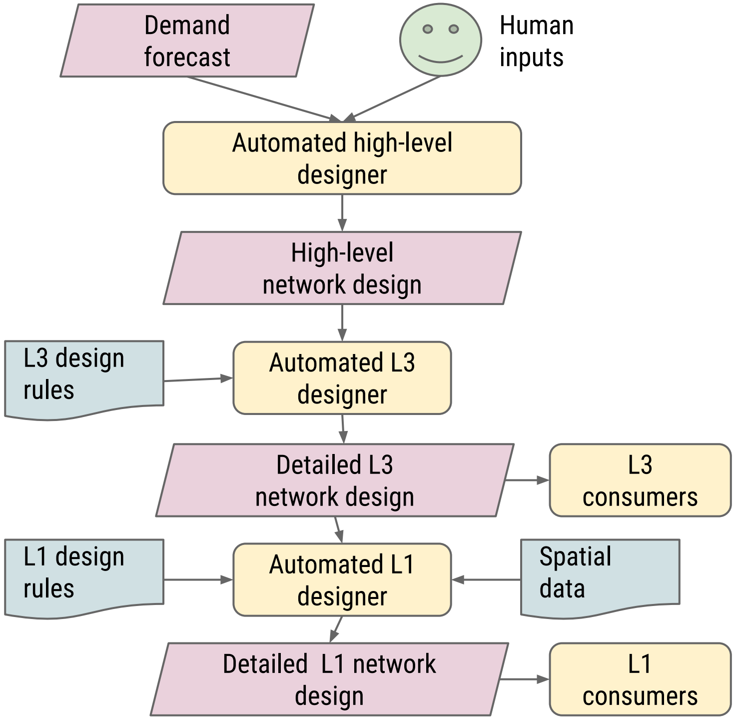
- MALT schema needs to continually evolve

We use multiple processes to manage evolution:

- curation of schema changes via expert "review board" + a written *Style Guide*
- versioned "profiles" to further constrain schema for specific parts of our networks
    - machine-checkable profile enforces contract between producers + consumers
    - automated model gen allows producers to create same data for multiple profiles
- "canned queries" insulate most consumers from much of our evolution

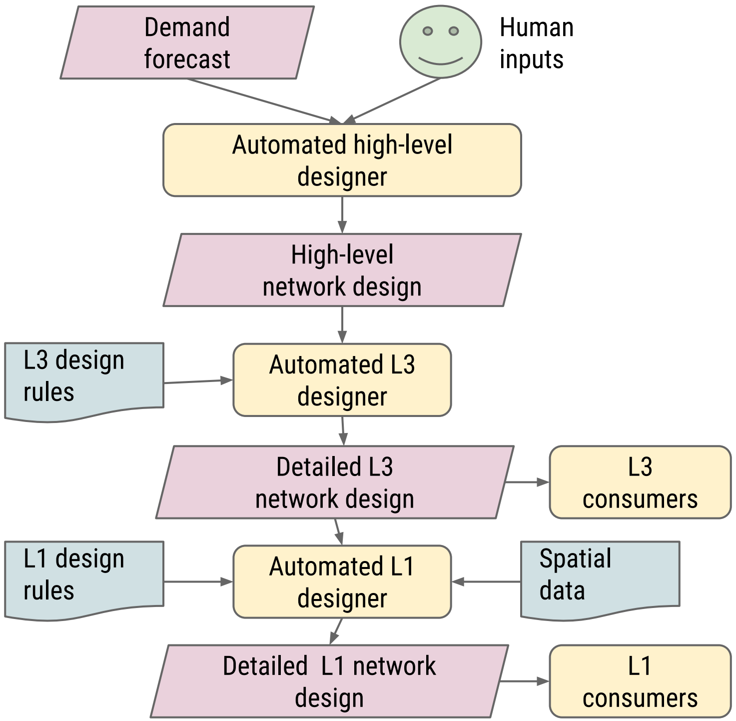
Abstraction is vital, but taxonomy is hard -- even for experts

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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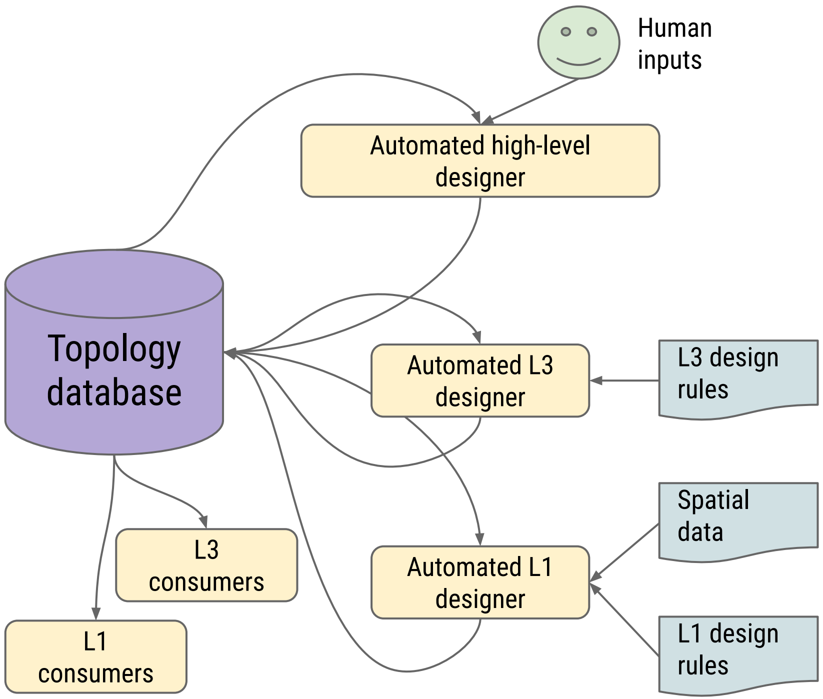
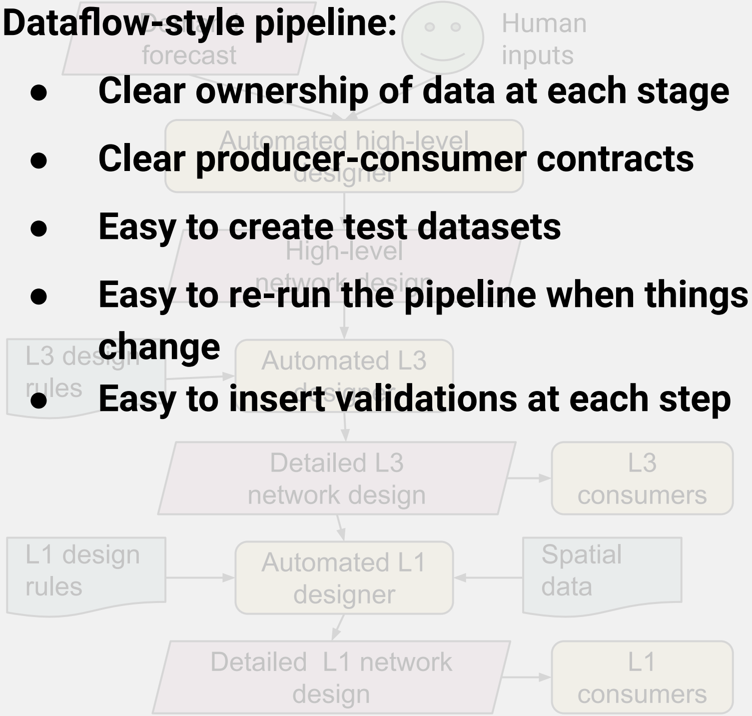


Database-style design pipeline

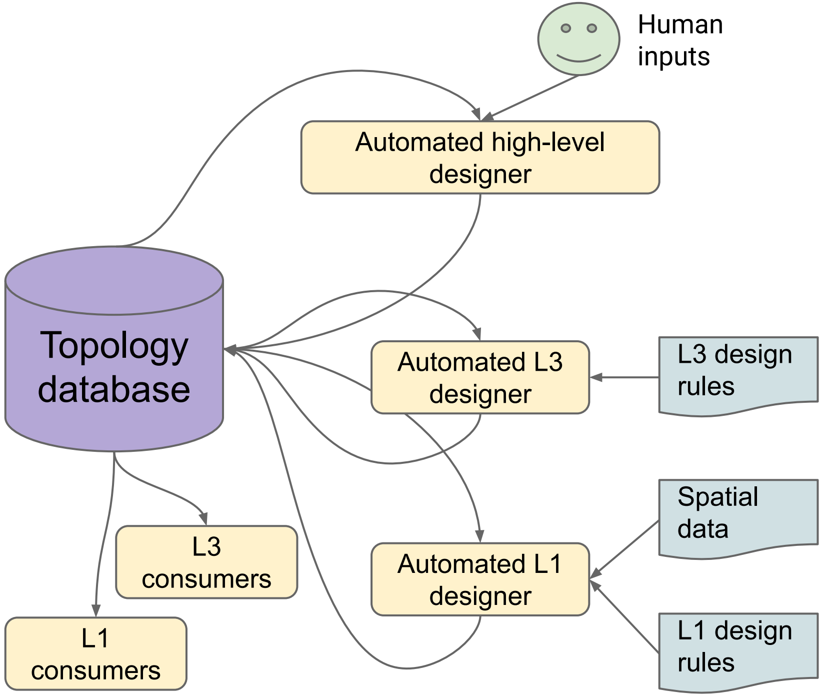
Why we prefer dataflow design pipelines to databases

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**



Dataflow-style design pipeline



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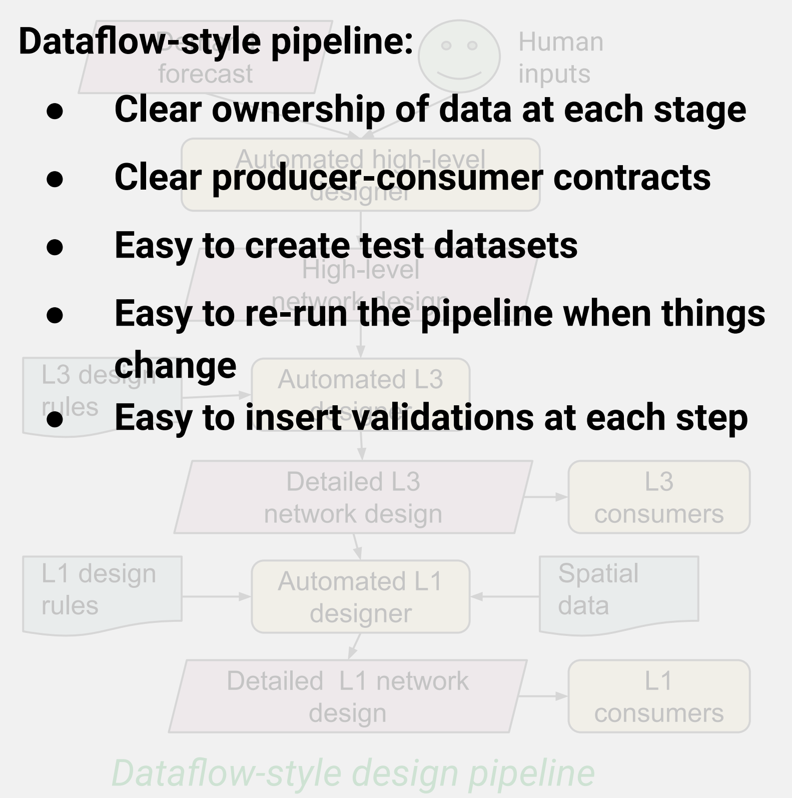
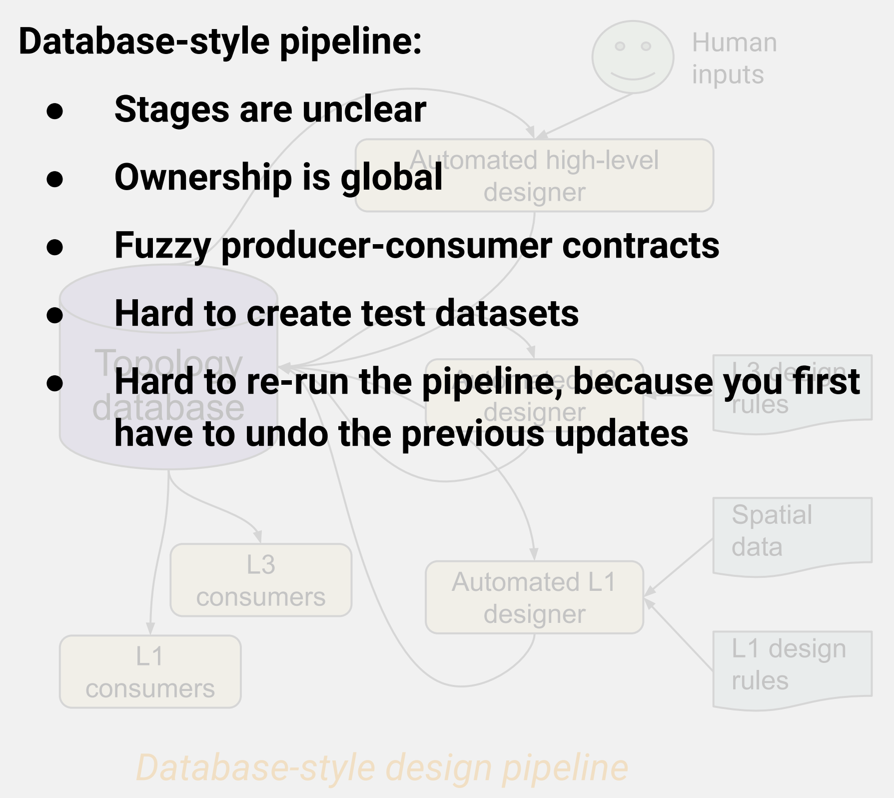


Database-style pipeline:

- **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**

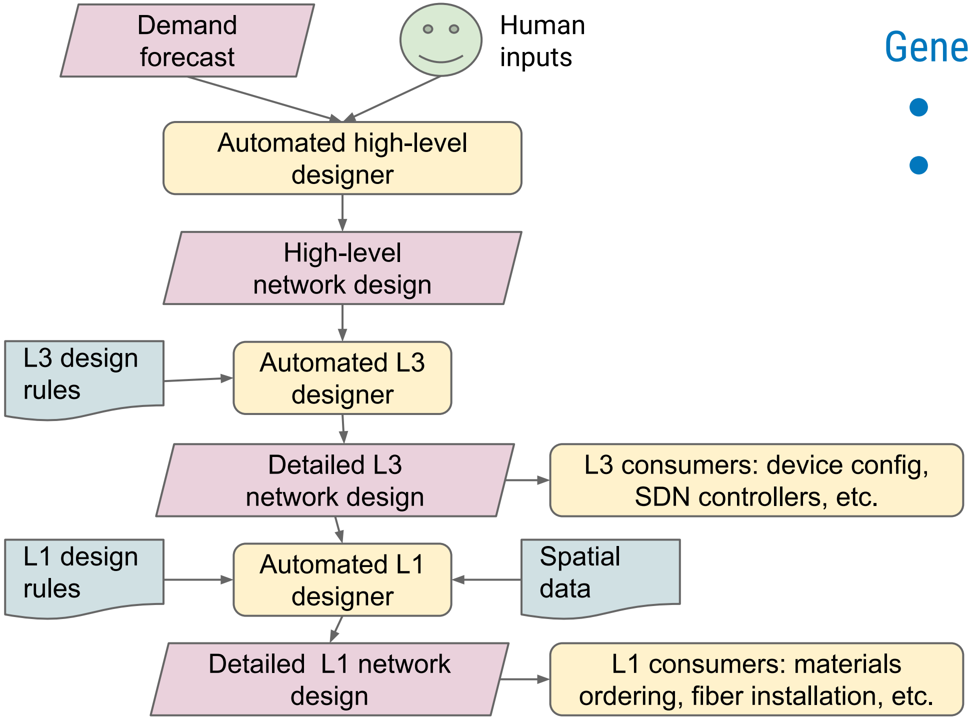


Thanks!

- 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 models tie together all of our network management automation
- network management: it's about the whole lifecycle, not just the running network

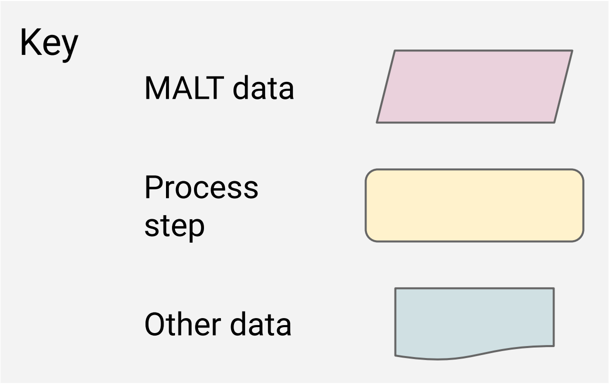
Additional material

Example: MALT for a multi-phase network design pipeline



Generate network designs automatically

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



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 } }
          }
        }
      }
    }
  }
}
```

Google