A model of Internet routing using semi-modules

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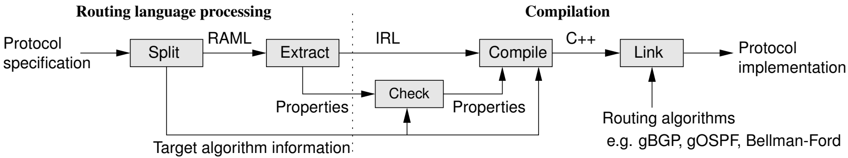
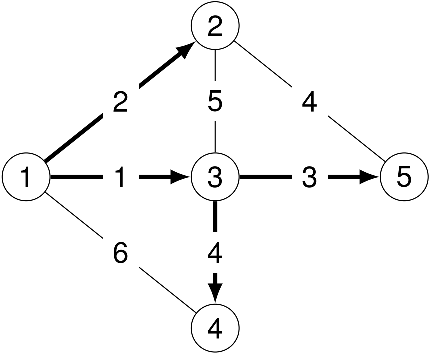
Context : Metarouting project



- Metric structure specified using the Routing Algebra Meta-Language (RAML).
- Algorithm picked from a library.
- Each algorithm is associated with properties it requires of a routing language (Example : Dijkstra requires a total order on metrics). Properties are automatically derived from RAML expressions.
- Problem : How can we understand the difference between forwarding and routing?

Shortest paths example over (min, $+$)



Bold arrows indicate the shortest-path tree rooted at 1.

$$\mathbf{A} = \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & 2 & 1 & 6 & \infty \\ 2 & 2 & \infty & 5 & \infty & 4 \\ 3 & 1 & 5 & \infty & 4 & 3 \\ 4 & 6 & \infty & 4 & \infty & \infty \\ 5 & \infty & 4 & 3 & \infty & \infty \end{array}$$

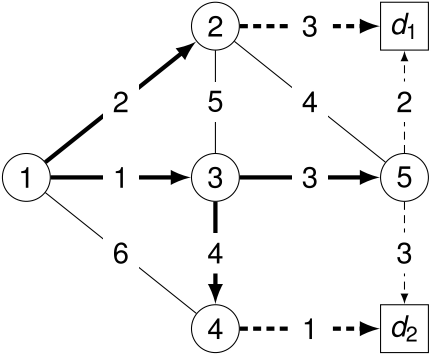
The adjacency matrix

$$\mathbf{R} = \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & 0 & 2 & 1 & 5 & 4 \\ 2 & 2 & 0 & 3 & 7 & 4 \\ 3 & 1 & 3 & 0 & 4 & 3 \\ 4 & 5 & 7 & 4 & 0 & 7 \\ 5 & 4 & 4 & 3 & 7 & 0 \end{array}$$

The routing matrix

matrix	solves
$\mathbf{A}^*$	$\mathbf{R} = (\mathbf{A} \otimes \mathbf{R}) \oplus \mathbf{I}$

Trivial example of forwarding = routing + mapping



$$\mathbf{M} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{cc} d_1 & d_2 \end{array} \\ \left[\begin{array}{cc} \infty & \infty \\ 3 & \infty \\ \infty & \infty \\ \infty & 1 \\ 2 & 3 \end{array}\right] \end{array}$$

Mapping matrix

matrix	solves
$\mathbf{A}^*$	$\mathbf{R} = (\mathbf{A} \otimes \mathbf{R}) \oplus \mathbf{I}$
$\mathbf{A}^*\mathbf{M}$	$\mathbf{F} = (\mathbf{A} \otimes \mathbf{F}) \oplus \mathbf{M}$

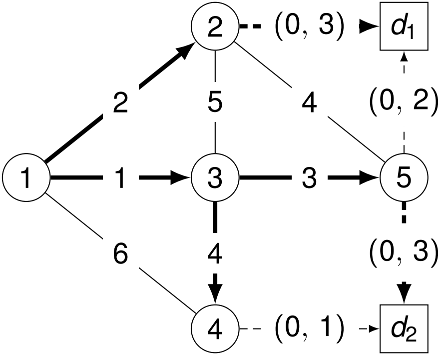
$$\mathbf{F} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{cc} d_1 & d_2 \end{array} \\ \left[\begin{array}{cc} 5 & 6 \\ 3 & 7 \\ 5 & 5 \\ 9 & 1 \\ 2 & 3 \end{array}\right] \end{array}$$

Forwarding matrix

Routing Matrix vs. Forwarding Matrix

- Inspired by the the Locator/ID split work
  - See Locator/ID Separation Protocol (LISP)
- Let's make a distinction between infrastructure nodes V and destinations D.
- Assume $V \cap D = \{\}$
- $\mathbf{M}$ is a $V \times D$ mapping matrix
  - $\mathbf{M}(v,\ d) \neq \infty$ means that destination (identifier) d is somehow attached to node (locator) v

More Interesting Example : Hot-Potato Idiom



$$\mathbf{M} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{cc} d_1 & d_2 \end{array} \\ \begin{bmatrix} \infty & \infty \\ (0,3) & \infty \\ \infty & \infty \\ \infty & (0,1) \\ (0,2) & (0,3) \end{bmatrix} \end{array}$$

Mapping matrix

$$\mathbf{F} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{cc} d_1 & d_2 \end{array} \\ \begin{bmatrix} (2,3) & (4,3) \\ (0,3) & (4,3) \\ (3,2) & (3,3) \\ (7,2) & (0,1) \\ (0,2) & (0,3) \end{bmatrix} \end{array}$$

Forwarding matrix

General Case

A $V \times V$ routing matrix solves an equation of the form

$$\mathbf{R} = (\mathbf{A} \otimes \mathbf{R}) \oplus \mathbf{I},$$

over structure S.

A $V \times D$ forwarding matrix is defined as

$$\mathbf{F} = \mathbf{R} \triangleright \mathbf{M},$$

over some structure $(N, \square, \triangleright)$, where $\triangleright \in (S \times N) \to N$.

forwarding = routing + mapping

Does this make sense?

$$\mathbf{F}(i,\ d) = (\mathbf{R} \rhd \mathbf{M})(i,\ d) = \sum_{q \in V}^{\Box} \mathbf{R}(i,\ q) \rhd \mathbf{M}(q,\ d).$$

- Once again we are leaving paths implicit in the construction.
- Forwarding paths are best routing paths to egress nodes, selected with respect $\Box$-minimality.
- $\Box$-minimality can be very different from selection involved in routing.

When we are lucky ...

matrix	solves
$\mathbf{A}^*$	$\mathbf{R} = (\mathbf{A} \otimes \mathbf{R}) \oplus \mathbf{I}$
$\mathbf{A}^* \rhd \mathbf{M}$	$\mathbf{F} = (\mathbf{A} \rhd \mathbf{F}) \square \mathbf{M}$

When does this happen?

When $(N, \ \square, \ \rhd)$ is a (left) semi-module over the semiring S.

(left) Semi-modules

- $(S, \oplus, \otimes, \overline{0}, \overline{1})$ is a semiring.

A (left) semi-module over S

Is a structure $(N, \Box, \triangleright, \overline{0}_N)$, where

- $(N, \Box, \overline{0}_N)$ is a commutative monoid
- $\triangleright$ is a function $\triangleright \in (S \times N) \to N$
- $\overline{0} \triangleright m = \overline{0}_N$
- $s \triangleright \overline{0}_N = \overline{0}_N$
- $\overline{1} \triangleright m = m$

and distributivity holds,

$$\begin{array}{lcrcl} \text{LD} & : & s \triangleright (m \Box n) & = & (s \triangleright m) \Box (s \triangleright n) \\ \text{RD} & : & (s \oplus t) \triangleright m & = & (s \triangleright m) \Box (t \triangleright m) \end{array}$$

Example : Hot-Potato

S idempotent and selective

$$
\begin{aligned}
S &= (S,\ \oplus_S,\ \otimes_S) \\
T &= (T,\ \oplus_T,\ \otimes_T) \\
\rhd_{\mathrm{fst}} &\in S \times (S \times T) \to (S \times T) \\
s_1 \rhd_{\mathrm{fst}} (s_2,\ t) &= (s_1 \otimes_S s_2,\ t)
\end{aligned}
$$

$$\mathrm{Hot}(S,\ T) = (S \times T,\ \vec{\oplus},\ \rhd_{\mathrm{fst}}),$$

where $\vec{\oplus}$ is the (left) lexicographic product of $\oplus_S$ and $\oplus_T$.

Define $\rhd_{\mathrm{hp}}$ on matrices

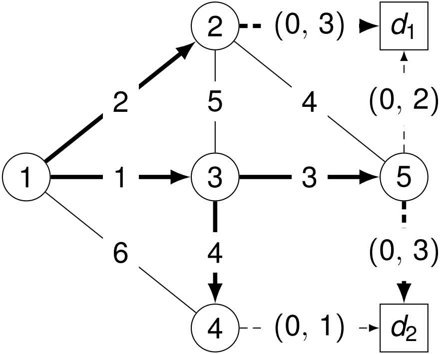
$$(\mathbf{R} \rhd_{\mathrm{hp}} \mathbf{M})(i,\ d) = \sum_{q \in V}^{\vec{\oplus}} \mathbf{R}(i,\ q) \rhd_{\mathrm{fst}} \mathbf{M}(q,\ d)$$

Sanity Check : does this implement hot-potato?

Define M to be simple if either $\mathbf{M}(v, d) = (1_S, t)$ or $\mathbf{M}(v, d) = (\infty_S, \infty_T)$.

$$
\begin{aligned}
& (\mathbf{R} \rhd_{\mathrm{hp}} \mathbf{M})(i, d) \\
= \; & \sum_{q \in V}^{\vec{\oplus}} \mathbf{R}(i, q) \rhd_{\mathrm{fst}} \mathbf{M}(q, d) \\
= \; & \sum_{\substack{q \in V \\ \mathbf{M}(q, d) = (s, t)}}^{\vec{\oplus}} (\mathbf{R}(i, q) \otimes_S s, t) \\
= \; & \sum_{\substack{q \in V \\ \mathbf{M}(q, d) = (1_S, t)}}^{\vec{\oplus}} (\mathbf{R}(i, q), t) \qquad \text{(if } M \text{ is simple)}
\end{aligned}
$$

Example of *hot-potato* forwarding



$$\mathbf{M} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{cc} d_1 & d_2 \\ \left[\begin{array}{c} \infty \\ (0,3) \\ \infty \\ \infty \\ (0,2) \end{array}\right. & \left.\begin{array}{c} \infty \\ \infty \\ \infty \\ (0,1) \\ (0,3) \end{array}\right] \end{array}$$

Mapping matrix

$$\mathbf{F} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{cc} d_1 & d_2 \\ \left[\begin{array}{c} (2,3) \\ (0,3) \\ (3,2) \\ (7,2) \\ (0,2) \end{array}\right. & \left.\begin{array}{c} (4,3) \\ (4,3) \\ (3,3) \\ (0,1) \\ (0,3) \end{array}\right] \end{array}$$

Forwarding matrix

matrix	solves
$\mathbf{A}^*$	$\mathbf{R} = (\mathbf{A} \otimes \mathbf{R}) \oplus \mathbf{I}$
$\mathbf{A}^* \rhd_{\mathrm{hp}} \mathbf{M}$	$\mathbf{F} = (\mathbf{A} \rhd_{\mathrm{hp}} \mathbf{F}) \vec{\oplus} \mathbf{M}$

Example : Cold-Potato

T idempotent and selective

$$\begin{array}{rcl} S & = & (S,\ \oplus_S,\ \otimes_S) \\ T & = & (T,\ \oplus_T,\ \otimes_T) \\ \rhd_{\text{fst}} & \in & S \times (S \times T) \to (S \times T) \\ s_1 \rhd_{\text{fst}} (s_2,\ t) & = & (s_1 \otimes_S s_2,\ t) \end{array}$$

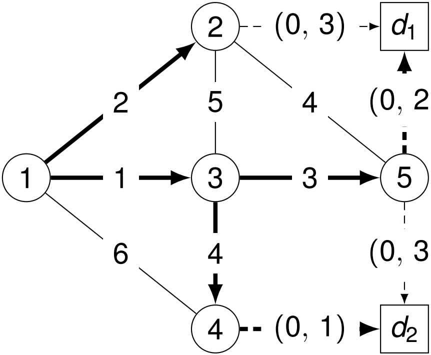
$$\text{Cold}(S,\ T) = (S \times T,\ \overleftarrow{\oplus},\ \rhd_{\text{fst}}),$$

where $\vec{\oplus}$ is the (left) lexicographic product of $\oplus_S$ and $\oplus_T$.

Define $\rhd_{\text{cp}}$ on matrices

$$(\mathbf{R} \rhd_{\text{cp}} \mathbf{M})(i,\ d) = \sum_{q \in V}^{\overleftarrow{\oplus}} \mathbf{R}(i,\ q) \rhd_{\text{fst}} \mathbf{M}(q,\ d)$$

Example of *cold-potato* forwarding



$$\mathbf{M} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{cc} d_1 & d_2 \end{array} \\ \begin{bmatrix} \infty & \infty \\ (0,\ 3) & \infty \\ \infty & \infty \\ \infty & (0,\ 1) \\ (0,\ 2) & (0,\ 3) \end{bmatrix} \end{array}$$

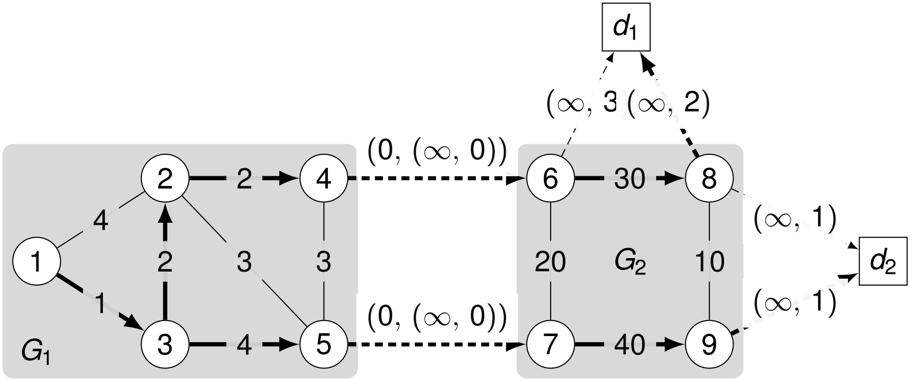
Mapping matrix

$$\mathbf{F} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{cc} d_1 & d_2 \end{array} \\ \begin{bmatrix} (4,\ 2) & (5,\ 1) \\ (4,\ 2) & (9,\ 1) \\ (3,\ 2) & (4,\ 1) \\ (7,\ 2) & (0,\ 1) \\ (0,\ 2) & (7,\ 1) \end{bmatrix} \end{array}$$

Forwarding matrix

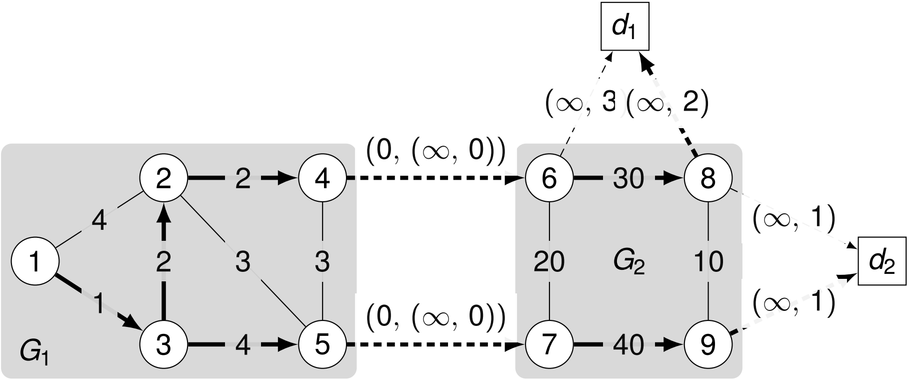
matrix	solves
$\mathbf{A}^*$	$\mathbf{R} = (\mathbf{A} \otimes \mathbf{R}) \oplus \mathbf{I}$
$\mathbf{A}^* \rhd_{cp} \mathbf{M}$	$\mathbf{F} = \mathbf{A} \rhd_{cp} \mathbf{F} \overleftarrow{\oplus} \mathbf{M}$

A simple example of route redistribution



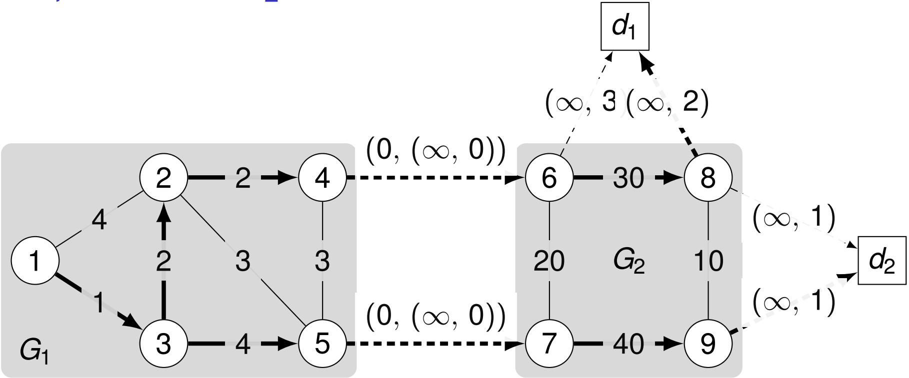
We will will use the routing and mapping of G_2 to construct a forwarding $\mathbf{F}_2$, that will be passed as a mapping to G_1 ...

A simple example of route redistribution



- G_2 is routing with the bandwidth semiring bw
- G_2 is forwarding with $\mathrm{Cold}(\mathrm{bw}, \mathrm{sp})$
- G_1 is routing with the bandwidth semiring sp
- G_1 is forwarding with $\mathrm{Hot}(\mathrm{sp}, \mathrm{Cold}(\mathrm{bw}, \mathrm{sp}))$

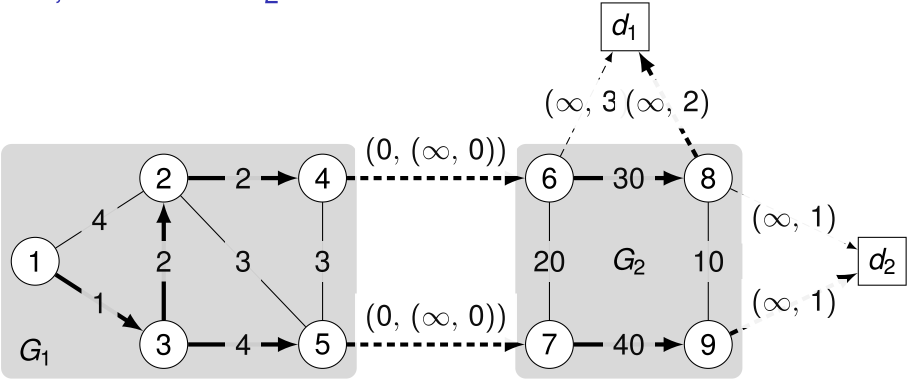
First, construct $\mathbf{F}_2$



$$\mathbf{R}_2 = \begin{array}{c} \\ 6 \\ 7 \\ 8 \\ 9 \end{array} \begin{array}{c} \begin{array}{cccc} 6 & 7 & 8 & 9 \end{array} \\ \begin{bmatrix} \infty & 20 & 30 & 20 \\ 20 & \infty & 20 & 40 \\ 30 & 20 & \infty & 20 \\ 20 & 40 & 20 & \infty \end{bmatrix} \end{array}$$

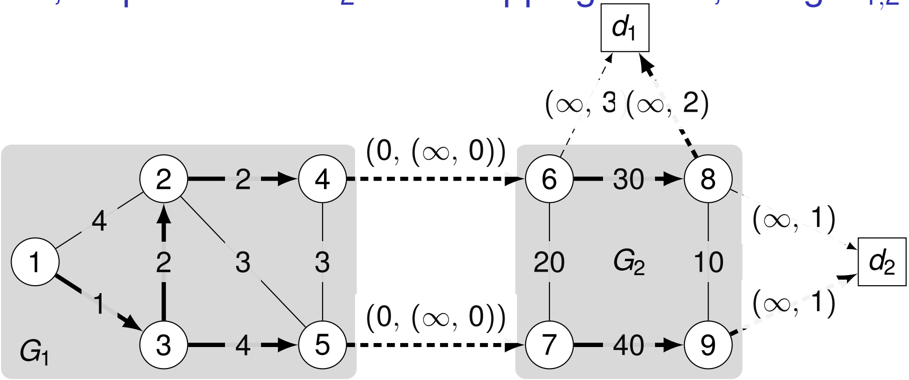
$$\mathbf{M}_2 = \begin{array}{c} \\ 6 \\ 7 \\ 8 \\ 9 \end{array} \begin{array}{c} \begin{array}{cc} d_1 & d_2 \end{array} \\ \begin{bmatrix} (\infty, 3) & \infty \\ \infty & \infty \\ (\infty, 2) & (\infty, 1) \\ \infty & (\infty, 1) \end{bmatrix} \end{array}$$

First, construct $\mathbf{F}_2$



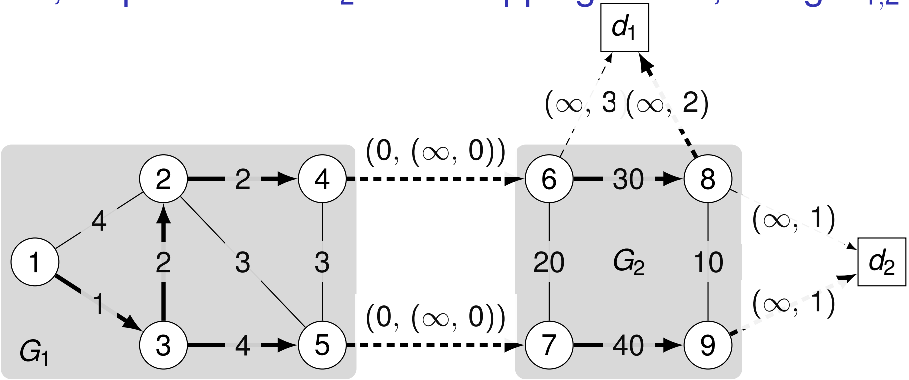
$$\mathbf{F}_2 = \mathbf{R}_2 \rhd_{\mathrm{cp}} \mathbf{M}_2 = \begin{array}{c} \\ 6 \\ 7 \\ 8 \\ 9 \end{array} \begin{array}{c} \begin{array}{cc} d_1 & d_2 \end{array} \\ \begin{bmatrix} (30, 2) & (30, 1) \\ (20, 2) & (40, 1) \\ (\infty, 2) & (\infty, 1) \\ (20, 2) & (\infty, 1) \end{bmatrix} \end{array}$$

Now, ship it over to G_2 as a mapping matrix, using $\mathbf{B}_{1,2}$



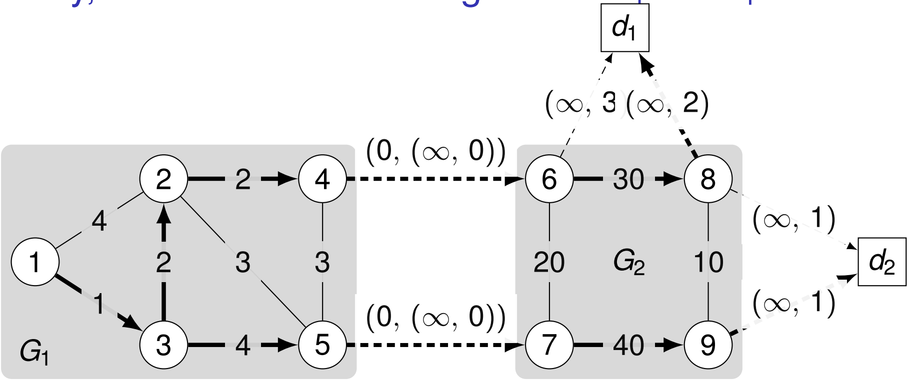
$$\mathbf{B}_{1,2} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{cccc} 6 & 7 & 8 & 9 \end{array} \\ \begin{bmatrix} \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty \\ (0, (\infty, 0)) & \infty & \infty & \infty \\ \infty & (0, (\infty, 0)) & \infty & \infty \end{bmatrix} \end{array}$$

Now, ship it over to G_2 as a mapping matrix, using $\mathbf{B}_{1,2}$



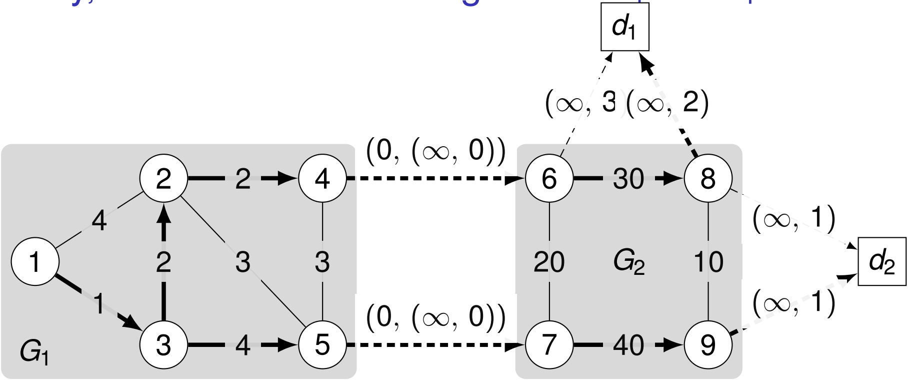
$$\mathbf{M}_1 = \mathbf{B}_{1,2} \lhd_{\mathrm{hp}} \mathbf{F}_2 = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{cc} d_1 & d_2 \\ \left[\begin{array}{cc} \infty & \infty \\ \infty & \infty \\ \infty & \infty \\ (0, (30, 2)) & (0, (30, 1)) \\ (0, (20, 2)) & (0, (40, 1)) \end{array}\right] \end{array}$$

Finally, construct a forwarding matrix $\mathbf{F}_1$ for G_1



$$\mathbf{R}_1 = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\ \begin{bmatrix} 0 & 3 & 1 & 5 & 5 \\ 3 & 0 & 2 & 2 & 3 \\ 1 & 2 & 0 & 4 & 4 \\ 5 & 2 & 4 & 0 & 3 \\ 5 & 3 & 4 & 3 & 0 \end{bmatrix} \end{array}$$

Finally, construct a forwarding matrix $\mathbf{F}_1$ for G_1



$$
\mathbf{F}_1 = \mathbf{R}_1 \rhd_{\mathrm{hp}} \mathbf{M}_1 =
\begin{array}{c}
 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5
\end{array}
\begin{array}{cc}
d_1 & d_2 \\
\left[\begin{array}{cc}
(5, (30, 2)) & (5, (40, 1)) \\
(2, (30, 2)) & (2, (30, 1)) \\
(4, (30, 2)) & (4, (40, 1)) \\
(0, (30, 2)) & (0, (30, 1)) \\
(0, (20, 2)) & (0, (40, 1))
\end{array}\right] &
\end{array}
$$

Research Questions

- How can we model Administrative Distance?
  - Can this be done in a way that preserves distributivity?
    - Conjecture : Nope!
- Need to integrate this model into our routing metalanguage.