An Albebraic Approach to Internet Routing
Lectures 01, 02, and 03

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Outline

(Tentative) Outline

- Lecture 01: Routing and Path problems
- Lecture 02: Semigroups and Order theory
- Lecture 03, 04, 05: Semirings
- Lecture 06: Beyond Semirings
- Lecture 07: Living without distribution?
- Lecture 08: Algorithmics
- Lecture 09 and 10: Advanced Constructions
- Lecture 11: Internet Routing I : OSPF, ISIS, RIP, EIGRP
- Lecture 12: Internet Routing II : route redistribution
- Lecture 13: Internet Routing III : interdomain (BGP)
- Lecture 14 and 15: Metarouting
- Lecture 16: Open questions and discussion

Background

Current Internet routing protocols exhibit several types of anomalies that can reduce network reliability and increase operational costs.

A very incomplete list of problems:

BGP No convergence guarantees [KRE00, GR01, MGWR02], wedgies [GH05]. Excessive table growth in backbone (see current work on Locator/ID separation in the RRG, for example [FFML09]).

IGPs The lack of options has resulted in some large networks using BGP as an IGP (see Chapter 5 of [ZB03] and Chapter 3 of [WMS05]).

RR and AD Recent work has illustrated some pitfalls of Route Redistribution (RR) and Administrative Distance (AD) [LXZ07, LXP+08, LXZ08].

We will return to these issues later in the term.

How did we get here?

- Internet protocols have evolved in a culture of ‘rough consensus and running code’ — pivotal to the success of the Internet due to the emphasis on interoperability.
- This has worked fairly well for data-transport and application-oriented protocols (IPv4, TCP, FTP, DNS, HTTP, ...)
- Then why are routing protocols so broken?

Why are routing protocols so broken?

- Routing protocols tend not to run on a user’s end system, but rather on specialized devices (routers) buried deep within a network’s infrastructure.
- The router market has been dominated by a few large companies — an environment that encourages proprietary extensions and the development of *de facto* standards.
- The expedient hack usually wins.
- And finally, let’s face it — routing is hard to get right.

What is to be done?

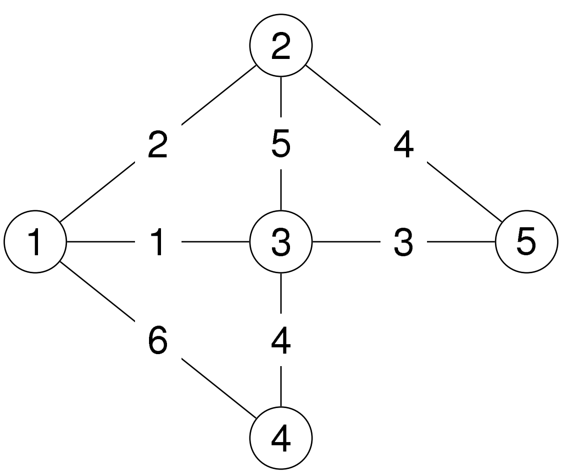
Central Thesis

The culture of the Internet has confounded two things that should be clearly distinguished — what problem is being solved and how it is being solved algorithmically.

Your challenge

- Think of yourself broadly as a Computer Scientist, not narrowly as a “networking person” ...
- Remember that the Internet did not come out of the established networking community! (See John Day’s wonderful book [Day08].) Why do we think the next generation network will??
- Routing research should be about more than just understanding the accidental complexity associated with artifacts pooped out by vendors.

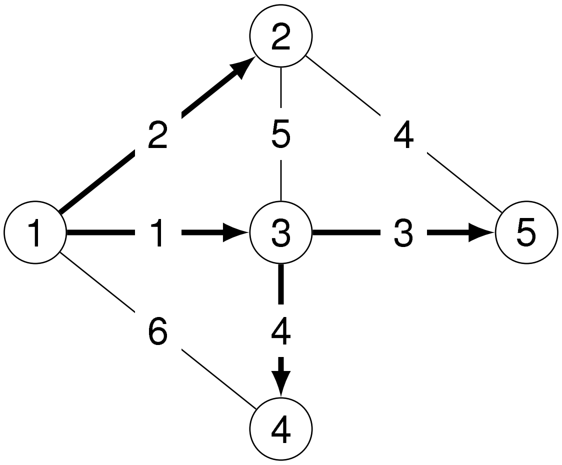
Shortest paths example, $(\mathbb{N}^{\infty}, \ \min, \ +)$



The adjacency matrix

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

Shortest paths example, $(\mathbb{N}^{\infty}, \ \min, \ +)$



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

The routing matrix

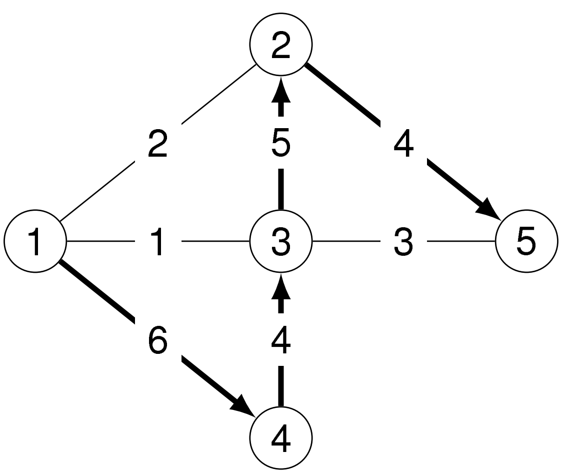
$$\mathbf{R} \quad = \quad \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\ \left[\begin{array}{ccccc} 0 & 2 & 1 & 5 & 4 \\ 2 & 0 & 3 & 7 & 4 \\ 1 & 3 & 0 & 4 & 3 \\ 5 & 7 & 4 & 0 & 7 \\ 4 & 4 & 3 & 7 & 0 \end{array} \right] \end{array}$$

Matrix **R** solves this global optimality problem:

$$\mathbf{R}(i, \ j) = \min_{p \in P(i, \ j)} w(p),$$

where $P(i, \ j)$ is the set of all paths from i to j.

Widest paths example, $(\mathbb{N}^{\infty}, \ \max, \ \min)$



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

The routing matrix

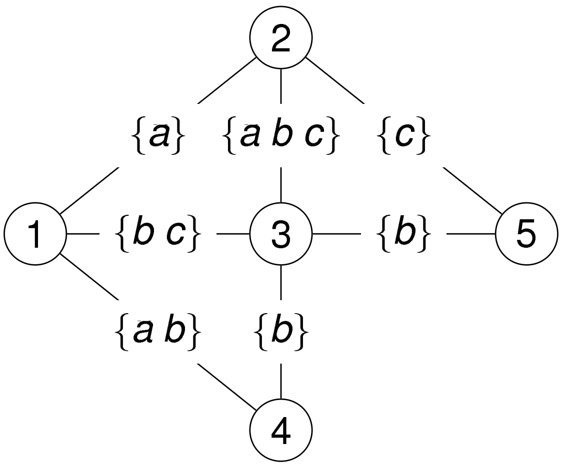
$$\mathbf{R} \quad = \quad \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\ \left[\begin{array}{ccccc} \infty & 4 & 4 & 6 & 4 \\ 4 & \infty & 5 & 4 & 4 \\ 4 & 5 & \infty & 4 & 4 \\ 6 & 4 & 4 & \infty & 4 \\ 4 & 4 & 4 & 4 & \infty \end{array} \right] \end{array}$$

Matrix **R** solves this global optimality problem:

$$\mathbf{R}(i, \ j) = \max_{p \in P(i, \ j)} w(p),$$

where $w(p)$ is now the minimal edge weight in p.

Strange example, $(2^{\{a,\ b,\ c\}},\ \cup,\ \cap)$



We want a Matrix **R** to solve this global optimality problem:

$$\mathbf{R}(i,\ j) = \bigcup_{p \in P(i,\ j)} w(p),$$

where $w(p)$ is now the intersection of all edge weights in p.

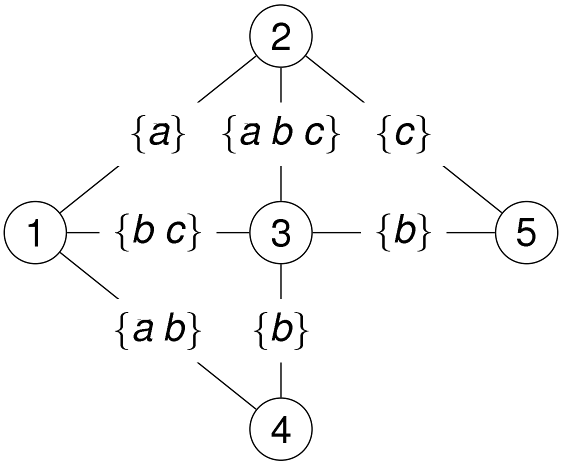
For $x \in \{a,\ b,\ c\}$, interpret $x \in \mathbf{R}(i,\ j)$ to mean that there is at least one path from i to j with x in every arc weight along the path.

Strange example, $(2^{\{a,\ b,\ c\}},\ \cup,\ \cap)$

The matrix **R**

	1	2	3	4	5
1	{a b c}	{a b}	{a b c}	{a b}	{b c}
2	{a b}	{a b c}	{a b c}	{a b}	{b c}
3	{a b c}	{a b c}	{a b c}	{a b}	{b c}
4	{a b}	{a b}	{a b}	{a b c}	{b}
5	{b c}	{b c}	{b c}	{b}	{a b c}

Another strange example, $(2^{\{a,\ b,\ c\}},\ \cap,\ \cup)$



We want matrix **R** to solve this global optimality problem:

$$\mathbf{R}(i,\ j) = \bigcap_{p \in P(i,\ j)} w(p),$$

where $w(p)$ is now the union of all edge weights in p.

For $x \in \{a,\ b,\ c\}$, interpret $x \in \mathbf{R}(i,\ j)$ to mean that every path from i to j has at least one arc with weight containing x.

Another strange example, $(2^{\{a,\ b,\ c\}},\ \cap,\ \cup)$

The matrix **R**

	1	2	3	4	5
1	$\{\}$	$\{\}$	$\{b\}$	$\{b\}$	$\{\}$
2	$\{\}$	$\{\}$	$\{b\}$	$\{b\}$	$\{\}$
3	$\{b\}$	$\{b\}$	$\{\}$	$\{b\}$	$\{b\}$
4	$\{b\}$	$\{b\}$	$\{b\}$	$\{\}$	$\{b\}$
5	$\{\}$	$\{\}$	$\{b\}$	$\{b\}$	$\{\}$

These structures are examples of Semirings

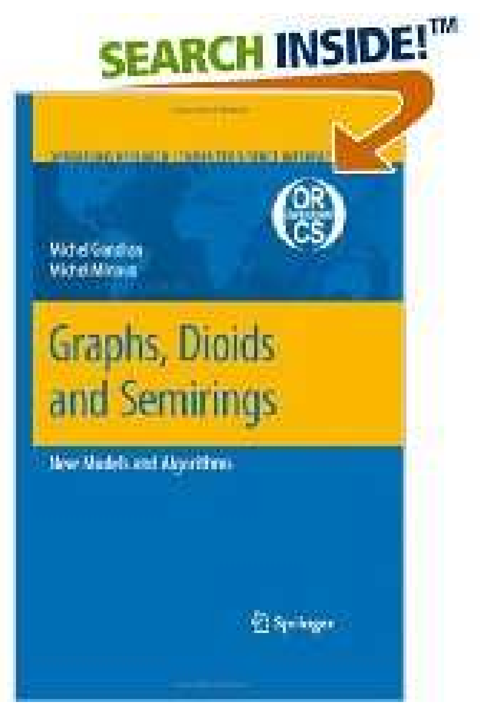
See [Car79, GM84, GM08]

name	S	$\oplus$,	$\otimes$	$\overline{0}$	$\overline{1}$	possible routing use
sp	$\mathbb{N}^{\infty}$	min	$+$	∞	0	minimum-weight routing
bw	$\mathbb{N}^{\infty}$	max	min	0	∞	greatest-capacity routing
rel	$[0, 1]$	max	$\times$	0	1	most-reliable routing
use	$\{0, 1\}$	max	min	0	1	usable-path routing
	2^W	$\cup$	$\cap$	$\{\}$	W	shared link attributes?
	2^W	$\cap$	$\cup$	W	$\{\}$	shared path attributes?

A wee bit of notation!

Symbol	Interpretation
$\mathbb{N}$	Natural numbers (starting with zero)
$\mathbb{N}^{\infty}$	Natural numbers, plus infinity
$\overline{0}$	Identity for $\oplus$
$\overline{1}$	Identity for $\otimes$

Recomended Reading



Outline

Semigroups

Definition (Semigroup)

A semigroup $(S, \oplus)$ is a non-empty set S with a binary operation such that

$$\text{ASSOCIATIVE} \quad : \quad a \oplus (b \oplus c) = (a \oplus b) \oplus c$$

S	$\oplus$	where
$\mathbb{N}^{\infty}$	min	
$\mathbb{N}^{\infty}$	max	
$\mathbb{N}^{\infty}$	$+$	
2^W	$\cup$	
2^W	$\cap$	
S^*	$\circ$	$(abc \circ de = abcde)$
S	left	$(a \text{ left } b = a)$
S	right	$(a \text{ right } b = b)$

Special Elements

Definition

- $\alpha \in S$ is an identity if for all $a \in S$

$$a = \alpha \oplus a = a \oplus \alpha$$

- A semigroup is a monoid if it has an identity.
- ω is an annihilator if for all $a \in S$

$$\omega = \omega \oplus a = a \oplus \omega$$

S	$\oplus$	α	ω
$\mathbb{N}^{\infty}$	min	∞	0
$\mathbb{N}^{\infty}$	max	0	∞
$\mathbb{N}^{\infty}$	$+$	0	∞
2^W	$\cup$	$\{\}$	W
2^W	$\cap$	W	$\{\}$
S^*	$\circ$	ϵ	
S	left		
S	right		

Important Properties

Definition (Some Important Semigroup Properties)

$$\begin{array}{rcrcl} \text{COMMUTATIVE} & : & a \oplus b & = & b \oplus a \\ \text{SELECTIVE} & : & a \oplus b & \in & \{a, b\} \\ \text{IDEMPOTENT} & : & a \oplus a & = & a \end{array}$$

S	$\oplus$	COMMUTATIVE	SELECTIVE	IDEMPOTENT
$\mathbb{N}^{\infty}$	min	$\star$	$\star$	$\star$
$\mathbb{N}^{\infty}$	max	$\star$	$\star$	$\star$
$\mathbb{N}^{\infty}$	$+$	$\star$		
2^W	$\cup$	$\star$		$\star$
2^W	$\cap$	$\star$		$\star$
S^*	$\circ$			
S	left		$\star$	$\star$
S	right		$\star$	$\star$

Order Relations

We are interested in order relations $\leq \subseteq S \times S$

Definition (Important Order Properties)

$$\begin{array}{rcl} \text{REFLEXIVE} & : & a \leq a \\ \text{TRANSITIVE} & : & a \leq b \wedge b \leq c \rightarrow a \leq c \\ \text{ANTISYMMETRIC} & : & a \leq b \wedge b \leq a \rightarrow a = b \\ \text{TOTAL} & : & a \leq b \vee b \leq a \end{array}$$

	pre-order	partial order	preference order	total order
REFLEXIVE	⋆	⋆	⋆	⋆
TRANSITIVE	⋆	⋆	⋆	⋆
ANTISYMMETRIC		⋆		⋆
TOTAL			⋆	⋆

Canonical Pre-order of a Commutative Semigroup

Suppose $\oplus$ is commutative.

Definition (Canonical pre-orders)

$$\begin{array}{rcl} a \trianglelefteq^R_\oplus b & \equiv & \exists c \in S : b = a \oplus c \\ a \trianglelefteq^L_\oplus b & \equiv & \exists c \in S : a = b \oplus c \end{array}$$

Lemma (Sanity check)

Associativity of $\oplus$ implies that these relations are transitive.

Proof.

Note that $a \trianglelefteq^R_\oplus b$ means $\exists c_1 \in S : b = a \oplus c_1$, and $b \trianglelefteq^R_\oplus c$ means $\exists c_2 \in S : c = b \oplus c_2$. Letting $c_3 =$ we have $c = b \oplus c_2 = (a \oplus c_1) \oplus c_2 = a \oplus (c_1 \oplus c_2) = a \oplus c_3$. That is, $\exists c_3 / inS : c = a \oplus c_3$, so $a \trianglelefteq^R_\oplus c$. The proof for $\trianglelefteq^L_\oplus$ is similar. □

Canonically Ordered Semigroup

Definition (Canonically Ordered Semigroup)

A commutative semigroup $(S, \oplus)$ is canonically ordered when $a \trianglelefteq^{R}_{\oplus} c$ and $a \trianglelefteq^{L}_{\oplus} c$ are partial orders.

Definition (Groups)

A monoid is a group if for every $a \in S$ there exists a $a^{-1} \in S$ such that $a \oplus a^{-1} = a^{-1} \oplus a = \alpha$.

Canonically Ordered Semigroups vs. Groups

Lemma (THE BIG DIVIDE)

Only a trivial group is canonically ordered.

Proof.

If $a, b \in S$, then $a = \alpha_{\oplus} \oplus a = (b \oplus b^{-1}) \oplus a = b \oplus (b^{-1} \oplus a) = b \oplus c$, for $c = b^{-1} \oplus a$, so $a \trianglelefteq^{L}_{\oplus} b$. In a similar way, $b \trianglelefteq^{R}_{\oplus} a$. Therefore $a = b$. □

Natural Orders

Definition (Natural orders)

Let $(S, \oplus)$ be a simigroup.

$$a \leq^L_\oplus b \equiv a = a \oplus b$$
$$a \leq^R_\oplus b \equiv b = a \oplus b$$

Lemma

If $\oplus$ is commutative and idempotent, then $a \trianglelefteq^D_\oplus b \iff a \leq^D_\oplus b$, for $D \in \{R, L\}$.

Proof.

$$\begin{array}{rcl} a \trianglelefteq^R_\oplus b & \iff & b = a \oplus c = (a \oplus a) \oplus c = a \oplus (a \oplus c) \\ & = & a \oplus b \iff a \leq^R_\oplus b \\ a \trianglelefteq^L_\oplus b & \iff & a = b \oplus c = (b \oplus b) \oplus c = b \oplus (b \oplus c) \\ & = & b \oplus a = a \oplus b \iff a \leq^L_\oplus b \end{array}$$

Special elements and natural orders

Lemma (Natural Bounds)

- *If α exists, then for all a, $a \leq^L_\oplus \alpha$ and $\alpha \leq^R_\oplus$*
- *If ω exists, then for all a, $\omega \leq^L_\oplus a$ and $a \leq^R_\oplus \omega$*
- *If α and ω exist, then S is bounded.*

$$\begin{array}{ccccc} \omega & \leq^L_\oplus & a & \leq^L_\oplus & \alpha \\ \alpha & \leq^R_\oplus & a & \leq^R_\oplus & \omega \end{array}$$

Remark (Thanks to Iljitsch van Beijnum)

Note that this means for $(\min, +)$ we have

$$\begin{array}{ccccc} 0 & \leq^L_{\min} & a & \leq^L_{\min} & \infty \\ \infty & \leq^R_{\min} & a & \leq^R_{\min} & 0 \end{array}$$

and still say that this is bounded, even though one might argue with the terminology!

Examples of special elements

S	$\oplus$	α	ω	$\leq_{\oplus}^{L}$	$\leq_{\oplus}^{R}$
$\mathbb{N} \cup \{\infty\}$	min	∞	0	$\leq$	$\geq$
$\mathbb{N} \cup \{\infty\}$	max	0	∞	$\geq$	$\leq$
$\mathcal{P}(W)$	$\cup$	$\{\}$	W	$\supseteq$	$\subseteq$
$\mathcal{P}(W)$	$\cap$	W	$\{\}$	$\subseteq$	$\supseteq$

Property Management

Lemma

Let $D \in \{R, L\}$.

1. $\text{IDEMPOTENT}((S, \oplus)) \iff \text{REFLEXIVE}((S, \leq_{\oplus}^{D}))$
2. $\text{COMMUTATIVE}((S, \oplus)) \implies \text{ANTISYMMETRIC}((S, \leq_{\oplus}^{D}))$
3. $\text{SELECTIVE}((S, \oplus)) \iff \text{TOTAL}((S, \leq_{\oplus}^{D}))$

Proof.

1. $a \leq_{\oplus}^{D} a \iff a = a \oplus a,$
2. $a \leq_{\oplus}^{L} b \wedge a \leq_{\oplus}^{L} b \iff a = a \oplus b \wedge b = b \oplus a \implies a = b$
3. $a = a \oplus b \vee b = a \oplus b \iff a \leq_{\oplus}^{L} b \vee b \leq_{\oplus}^{R} a$

□

Lexicographic Product of Semigroups

Definition (Lexicographic product semigroup (from [Gur08]))

Suppose S is commutative idempotent semigroup and T be a monoid. The lexicographic product is denoted $(S, \oplus_S) \vec{\times} (T, \oplus_T) = (S \times T, \oplus)$, where $\vec{\oplus} = \oplus_S \vec{\times} \oplus_T$ is defined as

$$(s_1, t_1) \vec{\oplus} (s_2, t_2) = \begin{cases} (s_1 \oplus_S s_2, t_1 \oplus_T t_2) & s_1 = s_1 \oplus_S s_2 = s_2 \\ (s_1 \oplus_S s_2, t_1) & s_1 = s_1 \oplus_S s_2 \neq s_2 \\ (s_1 \oplus_S s_2, t_2) & s_1 \neq s_1 \oplus_S s_2 = s_2 \\ (s_1 \oplus_S s_2, \overline{0}_T) & \text{otherwise.} \end{cases}$$

Direct Product of Semigroups

Let $(S, \oplus_S)$ and $(T, \oplus_T)$ be semigroups.

Definition (Direct product semigroup)

The direct product is denoted $(S, \oplus_S) \times (T, \oplus_T) = (S \times T, \oplus)$, where $\oplus = \oplus_S \times \oplus_T$ is defined as

$$(s_1, t_1) \oplus (s_2, t_2) = (s_1 \oplus_S s_2, \ t_1 \oplus_T t_2).$$

Outline

Semirings

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

- $(S, \oplus, \overline{0})$ is a commutative monoid
- $(S, \otimes, \overline{1})$ is a monoid
- $\overline{0}$ is an annihilator for $\otimes$

and distributivity holds,

$$\begin{array}{lcrcl} \text{LD} & : & a \otimes (b \oplus c) & = & (a \otimes b) \oplus (a \otimes c) \\ \text{RD} & : & (a \oplus b) \otimes c & = & (a \otimes c) \oplus (b \otimes c) \end{array}$$

Encoding path problems

- $(S, \oplus, \otimes, \overline{0}, \overline{1})$ a semiring
- $G = (V, E)$ a directed graph
- $w \in E \rightarrow S$ a weight function

Path weight

The *weight* of a path $p = i_1, i_2, i_3, \cdots, i_k$ is

$$w(p) = w(i_1, i_2) \otimes w(i_2, i_3) \otimes \cdots \otimes w(i_{k-1}, i_k).$$

The empty path is given the weight $\overline{1}$.

Adjacency matrix **A**

$$\mathbf{A}(i, j) = \begin{cases} w(i, j) & \text{if } (i, j) \in E, \\ \overline{0} & \text{otherwise} \end{cases}$$

The general problem of finding globally optimal paths

Given an adjacency matrix **A**, find **R** such that for all $i, j \in V$

$$\mathbf{R}(i, j) = \bigoplus_{p \in P(i, j)} w(p)$$

How can we solve this problem?

Lift semiring to matrices

- $(S, \oplus, \otimes, \overline{0}, \overline{1})$ a semiring
- Define the semiring of $n \times n$-matrices over S : $(\mathbb{M}_n(S), \oplus, \otimes, \mathbf{J}, \mathbf{I})$

$\oplus$ and $\otimes$

$$
\begin{aligned}
(\mathbf{A} \oplus \mathbf{B})(i, j) &= \mathbf{A}(i, j) \oplus \mathbf{B}(i, j) \\
(\mathbf{A} \otimes \mathbf{B})(i, j) &= \bigoplus_{1 \le q \le n} \mathbf{A}(i, q) \otimes \mathbf{B}(q, j)
\end{aligned}
$$

J and I

$$
\begin{aligned}
\mathbf{J}(i, j) &= \overline{0} \\
\mathbf{I}(i, j) &= \begin{cases} \overline{1} & (\text{if } i = j) \\ \overline{0} & (\text{otherwise}) \end{cases}
\end{aligned}
$$

$\mathbb{M}_n(S)$ is a semiring!

Check (left) distribution

$$\mathbf{A} \otimes (\mathbf{B} \oplus \mathbf{C}) = (\mathbf{A} \otimes \mathbf{B}) \oplus (\mathbf{A} \otimes \mathbf{C})$$

$$
\begin{aligned}
& (\mathbf{A} \otimes (\mathbf{B} \oplus \mathbf{C}))(i, j) \\
= & \bigoplus_{1 \le q \le n} \mathbf{A}(i, q) \otimes (\mathbf{B} \oplus \mathbf{C})(q, j) \\
= & \bigoplus_{1 \le q \le n} \mathbf{A}(i, q) \otimes (\mathbf{B}(q, j) \oplus \mathbf{C}(q, j)) \\
= & \bigoplus_{1 \le q \le n} (\mathbf{A}(i, q) \otimes \mathbf{B}(q, j)) \oplus (\mathbf{A}(i, q) \otimes \mathbf{C}(q, j)) \\
= & (\bigoplus_{1 \le q \le n} \mathbf{A}(i, q) \otimes \mathbf{B}(q, j)) \oplus (\bigoplus_{1 \le q \le n} \mathbf{A}(i, q) \otimes \mathbf{C}(q, j)) \\
= & ((\mathbf{A} \otimes \mathbf{B}) \oplus (\mathbf{A} \otimes \mathbf{C}))(i, j)
\end{aligned}
$$

Powers and closure

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

Powers, a^k

$$\begin{aligned} a^0 &= \overline{1} \\ a^{k+1} &= a \otimes a^k \end{aligned}$$

Closure, a^*

$$\begin{aligned} a^{(k)} &= a^0 \oplus a^1 \oplus a^2 \oplus \cdots \oplus a^k \\ a^* &= a^0 \oplus a^1 \oplus a^2 \oplus \cdots \oplus a^k \oplus \cdots \end{aligned}$$

Definition (q stability)

If there exists a q such that $a^{(q)} = a^{(q+1)}$, then a is q-stable. Therefore, $a^* = a^{(q)}$, assuming $\oplus$ is idempotent.

Fact 1

If $\overline{1}$ is an annihiltor for $\oplus$, then every $a \in S$ is 0-stable!

On the matrix semiring

Matrix powers, $\mathbf{A}^k$

$$\begin{aligned} \mathbf{A}^0 &= \mathbf{I} \\ \mathbf{A}^{k+1} &= \mathbf{A} \otimes \mathbf{A}^k \end{aligned}$$

Closure, $\mathbf{A}^*$

$$\begin{aligned} \mathbf{A}^{(k)} &= \mathbf{I} \oplus \mathbf{A}^1 \oplus \mathbf{A}^2 \oplus \cdots \oplus \mathbf{A}^k \\ \mathbf{A}^* &= \mathbf{I} \oplus \mathbf{A}^1 \oplus \mathbf{A}^2 \oplus \cdots \oplus \mathbf{A}^k \oplus \cdots \end{aligned}$$

Note: $\mathbf{A}^*$ might not exist (sum may not converge)

Fact 2

If S is 0-stable, then $\mathbb{M}_n(S)$ is $(n-1)$-stable. That is,

$$\mathbf{A}^* = \mathbf{A}^{(n-1)} = \mathbf{I} \oplus \mathbf{A}^1 \oplus \mathbf{A}^2 \oplus \cdots \oplus \mathbf{A}^{n-1}$$

Computing optimal paths

- Let $P(i, j)$ be the set of paths from i to j.
- Let $P^k(i, j)$ be the set of paths from i to j with exactly k arcs.
- Let $P^{(k)}(i, j)$ be the set of paths from i to j with at most k arcs.

Theorem

$$\begin{array}{lrcl} (1) & \mathbf{A}^k(i,\ j) & = & \bigoplus_{p \in P^k(i,\ j)} w(p) \\ (2) & \mathbf{A}^{(k+1)}(i,\ j) & = & \bigoplus_{p \in P^{(k)}(i,\ j)} w(p) \\ (3) & \mathbf{A}^{(*)}(i,\ j) & = & \bigoplus_{p \in P(i,\ j)} w(p) \end{array}$$

Proof of (1)

By induction on k. Base Case: $k = 0$.

$$P^0(i,\ i) = \{\epsilon\},$$

so $\mathbf{A}^0(i\ , i) = \mathbf{I}(i,\ i) = \overline{1} = w(\epsilon)$.

And $i \neq j$ implies $P^0(i, j) = \{\}$. By convention

$$\bigoplus_{p \in \{\}} w(p) = \overline{0} = \mathbf{I}(i,\ j).$$

Proof of (1)

Induction step.

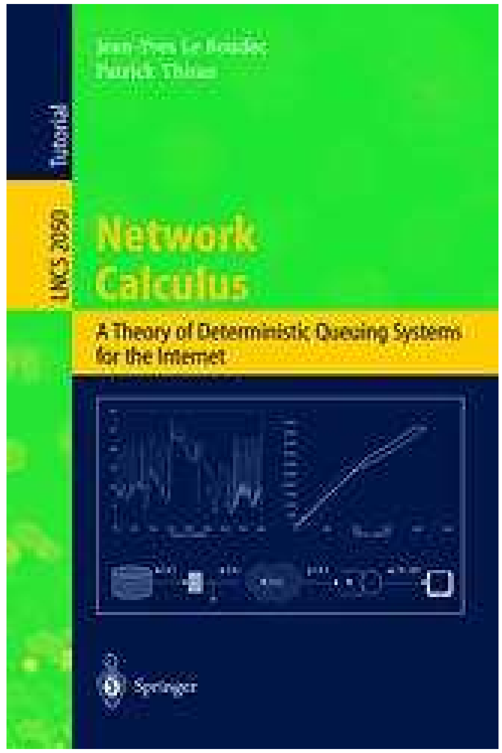
$$\begin{aligned}
\mathbf{A}^{k+1}(i, j) &= (\mathbf{A} \otimes \mathbf{A}^k)(i,\ j) \\
&= \bigoplus_{1 \leq q \leq n} \mathbf{A}(i,\ q) \otimes \mathbf{A}^k(q,\ j) \\
&= \bigoplus_{1 \leq q \leq n} \mathbf{A}(i,\ q) \otimes (\bigoplus_{p \in P^k(q,\ j)} w(p)) \\
&= \bigoplus_{1 \leq q \leq n} \bigoplus_{p \in P^k(q,\ j)} \mathbf{A}(i,\ q) \otimes w(p) \\
&= \bigoplus_{(i,\ q) \in E} \bigoplus_{p \in P^k(q, j)} w(i,\ q) \otimes w(p) \\
&= \bigoplus_{p \in P^{k+1}(i,\ j)} w(p)
\end{aligned}$$

Semirings have other applications in Networking

Network calculus [BT01]. For analyzing performance guarantees in networks. Traffic flows are subject to constraints imposed by the system components :

- link capacity
- traffic shapers (leaky buckets)
- congestion control
- background traffic

Algebraic means of expressing and analyzing these constraints starts with the min-plus semiring.



Lexicographic Semiring

$$(S,\ \oplus_S,\ \otimes_S)\ \vec{\times}\ (T,\ \oplus_T,\ \otimes_T) = (S \times T,\ \oplus_S\ \vec{\times}\ \oplus_T,\ \otimes_S \times \otimes_T)$$

Theorem ([Sai70, GG07, Gur08])

$$\text{LD}(S\ \vec{\times}\ T) \iff \text{LD}(S) \wedge \text{LD}(T) \wedge (\text{LC}(S) \vee \text{LK}(T))$$

Where

Property	Definition
LD	$\forall a, b, c : c \otimes (a \oplus b) = (c \otimes a) \oplus (c \otimes b)$
LC	$\forall a, b, c : c \otimes a = c \otimes b \implies a = b$
LK	$\forall a, b, c : c \otimes a = c \otimes b$

Return to examples

name	LD	LC	LK
sp	Yes	Yes	No
bw	Yes	No	No

So we have

$$\mathtt{LD}(\mathrm{sp} \vec{\times} \mathrm{bw})$$

and

$$\neg(\mathtt{LD}(\mathrm{bw} \vec{\times} \mathrm{sp}))$$

Exercise I

- Show that $(S, \oplus_S) \vec{\times} (T, \oplus_T)$ is associative.
- What are the natural orders associated with this construction? Explore.
- Prove Fact 1.
- Prove Fact 2.
- Finish the proof that $\mathbb{M}_n(S)$ is a semiring.

Outline

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