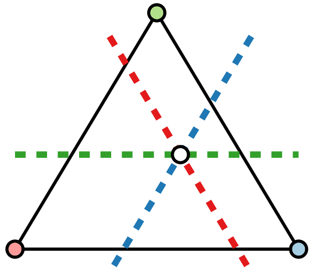
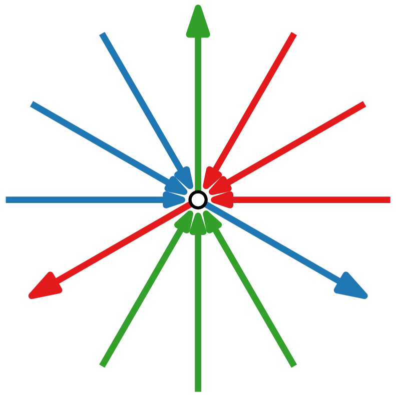
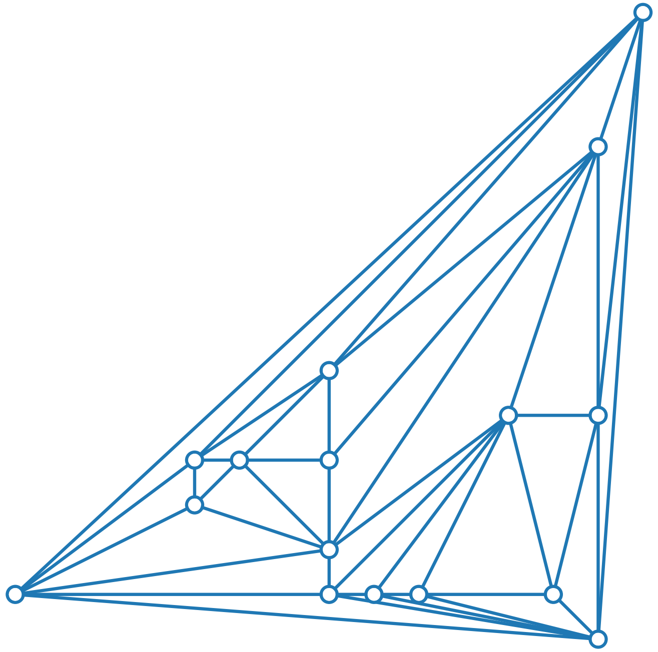
Universität Trier



Visualization of Graphs



Lecture 5:
Straight-Line Drawings of Planar Graphs II:
Schnyder Realizer



Part I:
Barycentric Representation

Philipp Kindermann

Planar Straight-Line Drawings

Theorem. [De Fraysseix, Pach, Pollack '90]
Every n-vertex planar graph has a planar straight-line drawing of size $(2n-4) \times (n-2)$.

Theorem. [Schnyder '90]
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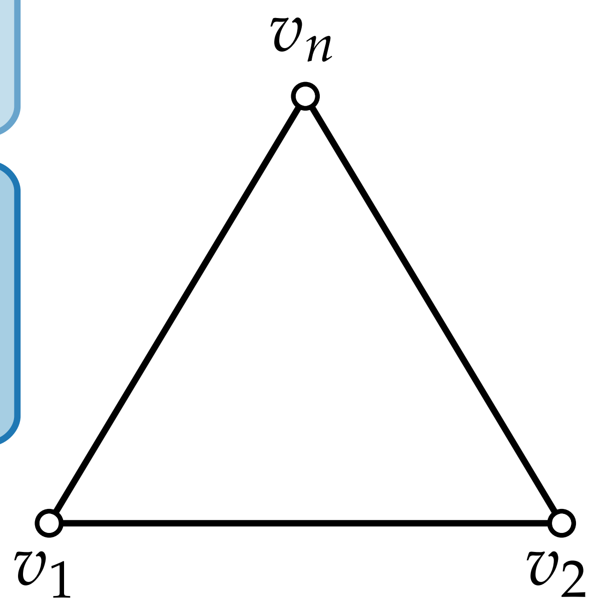

Idea.

- Fix outer triangle.

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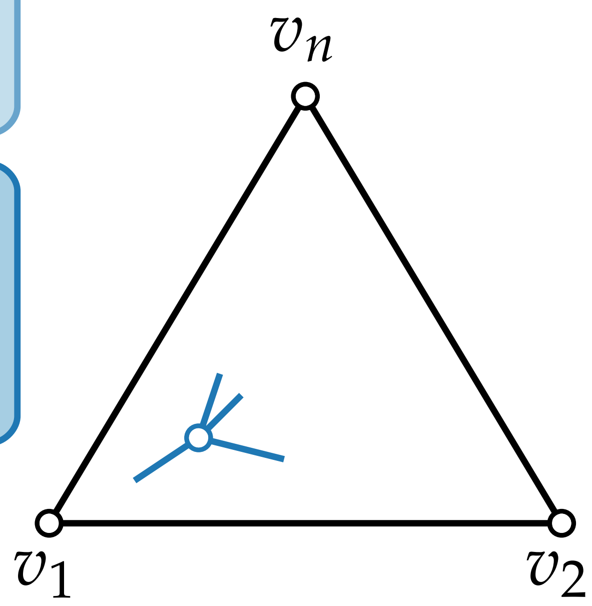

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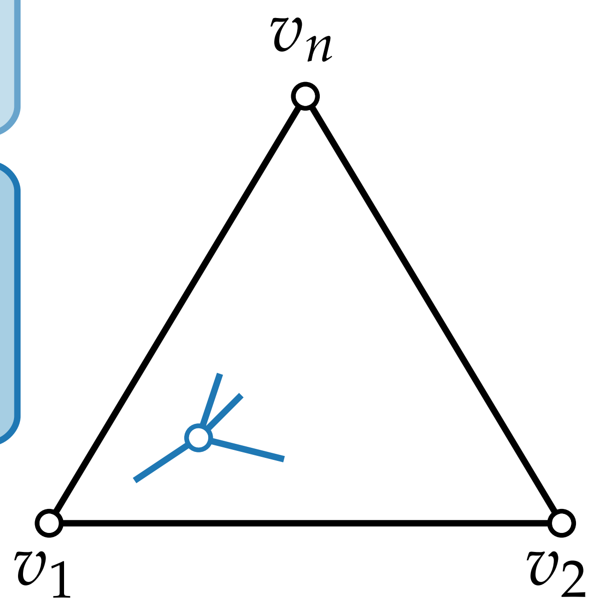

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- Fix outer triangle.
- Compute coordinates of inner vertices
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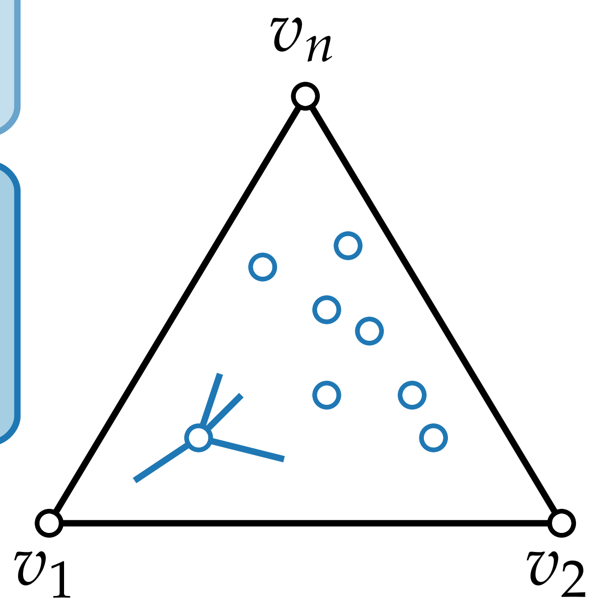

Idea.

- Fix outer triangle.
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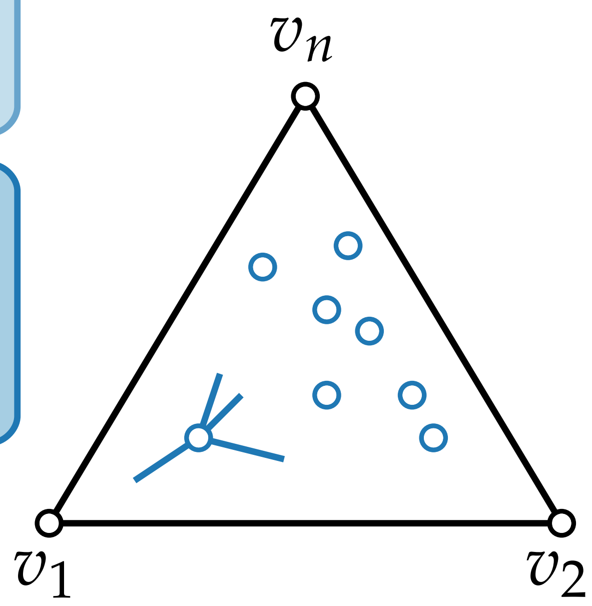

Idea.

- Fix outer triangle.
- Compute coordinates of inner vertices
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  - using weighted barycentric coordinates.

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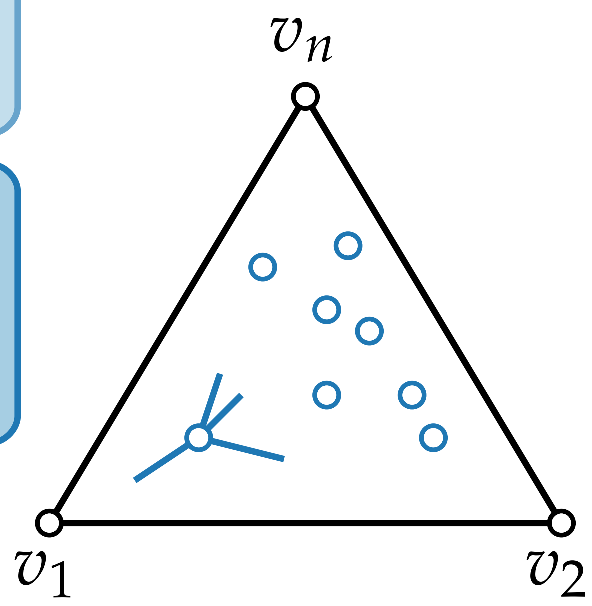

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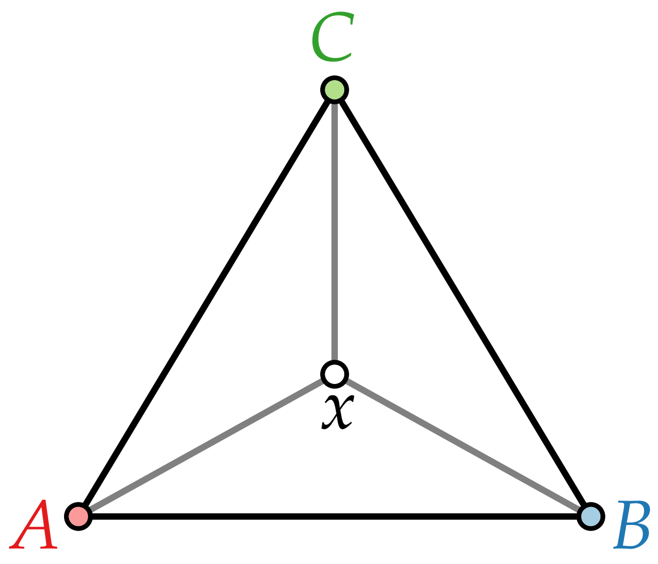
Barycentric Coordinates

Recall: barycenter$(x_1, \ldots, x_k) = \sum_{i=1}^{k} x_i / k$



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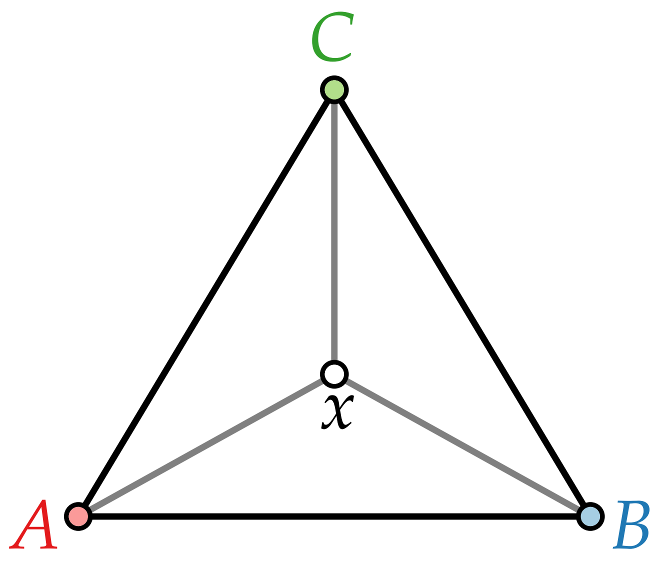

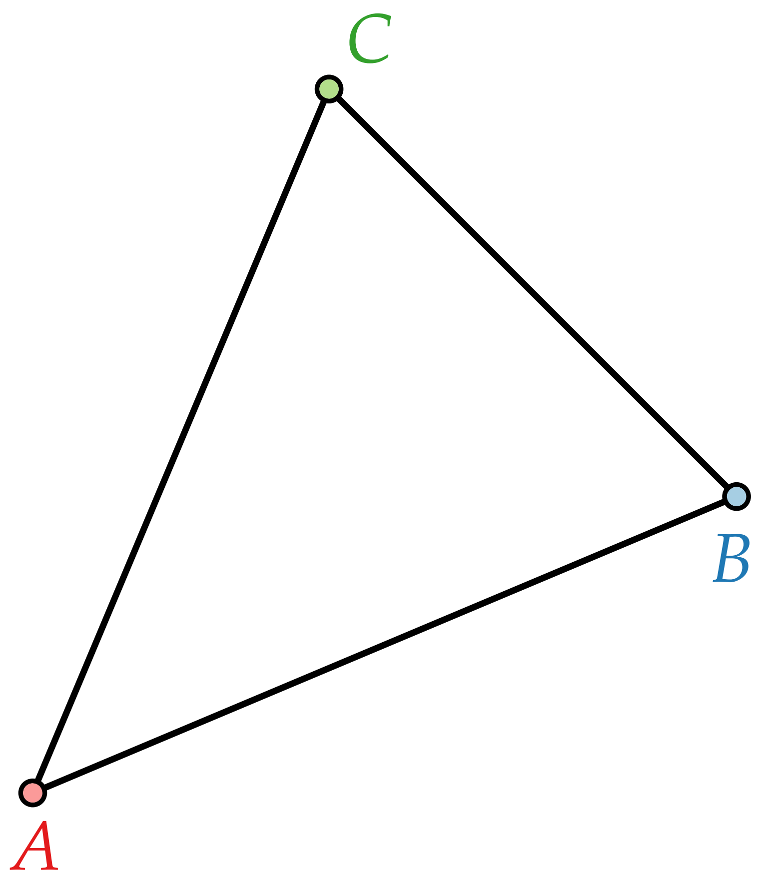

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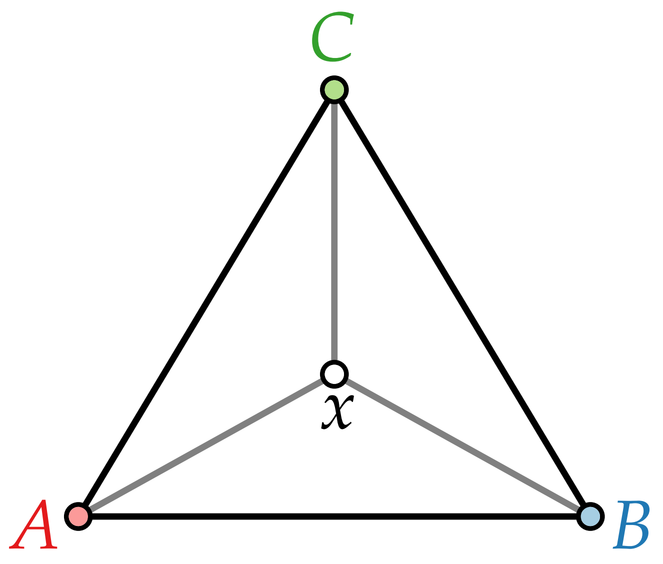
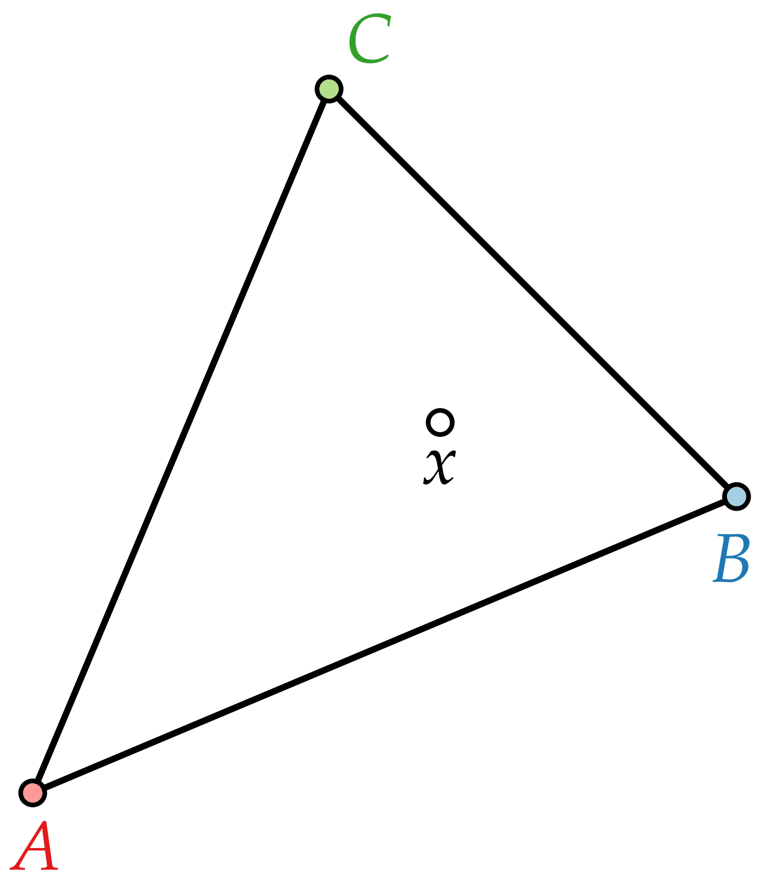
Let A, B, C form a triangle, let x lie inside $\triangle ABC$.





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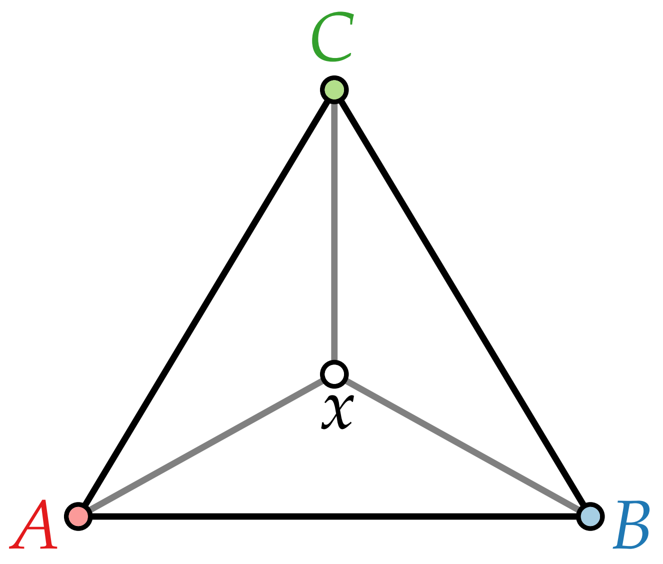

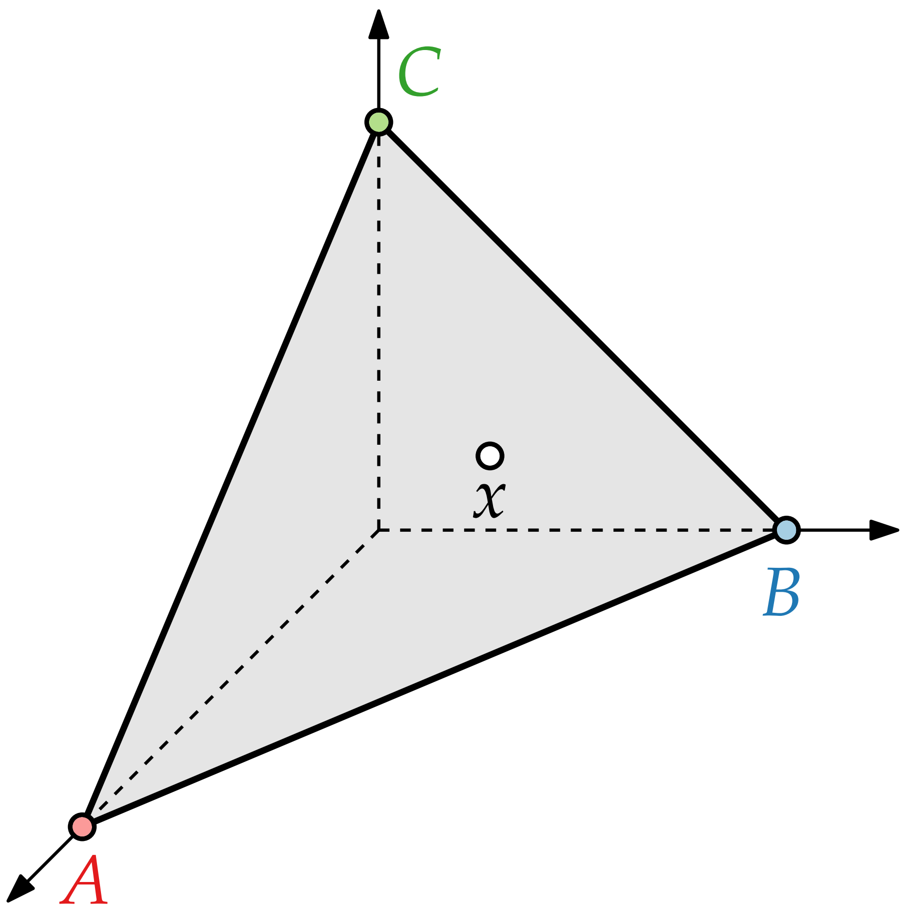

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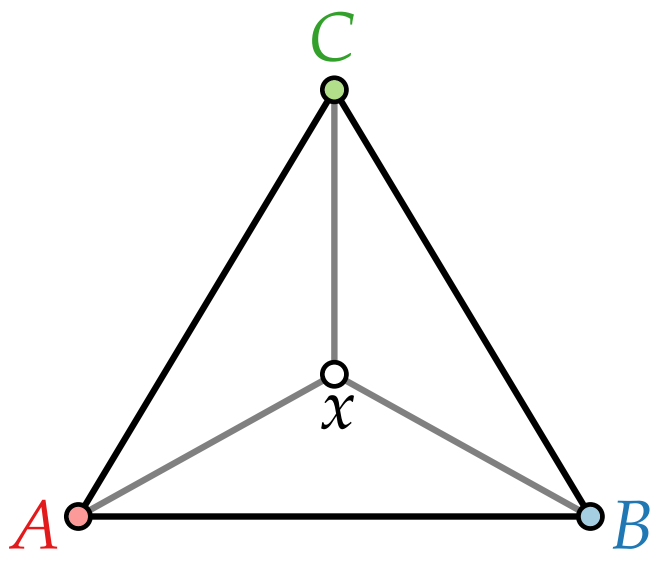

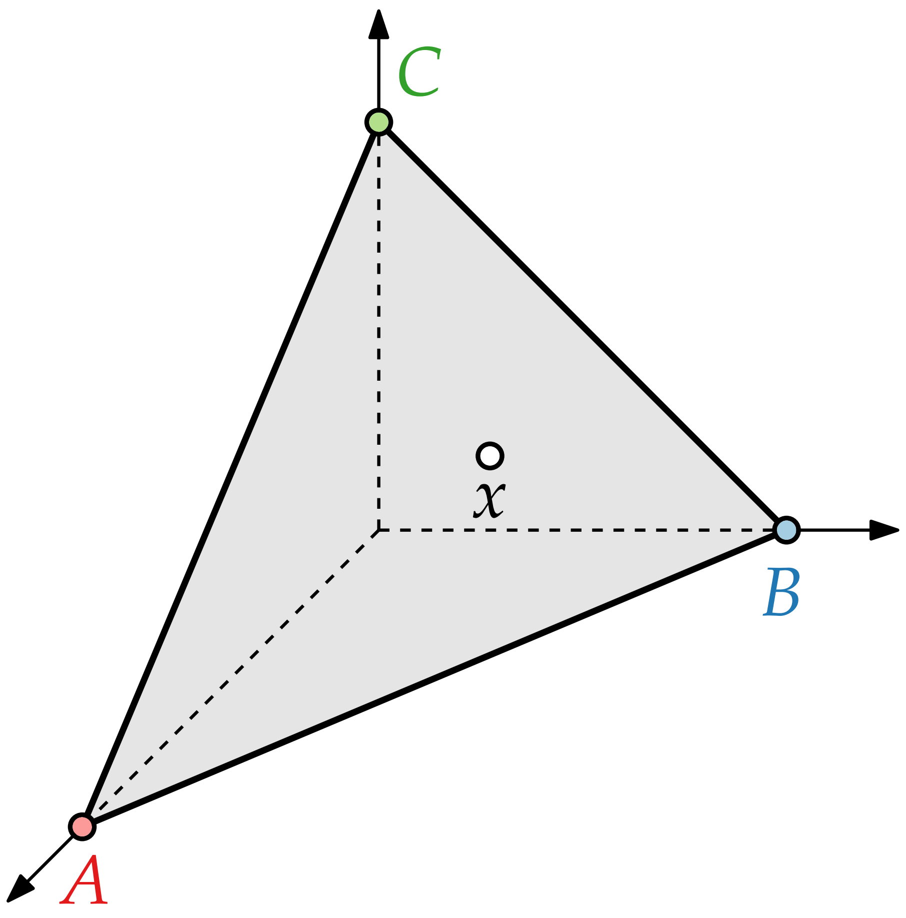

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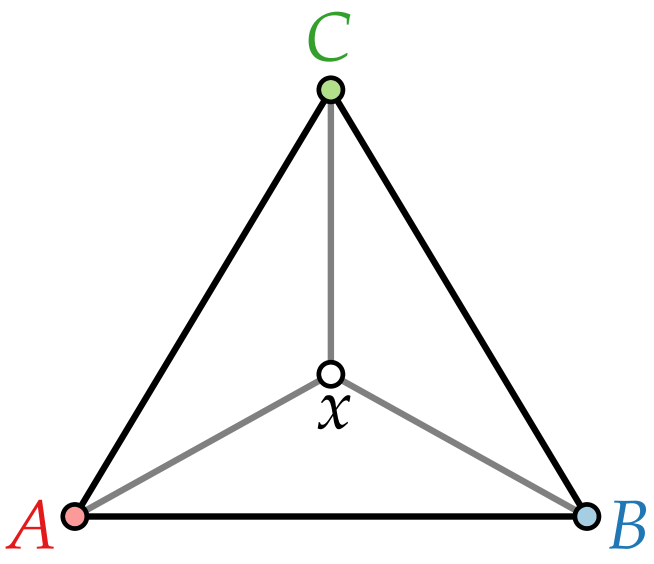

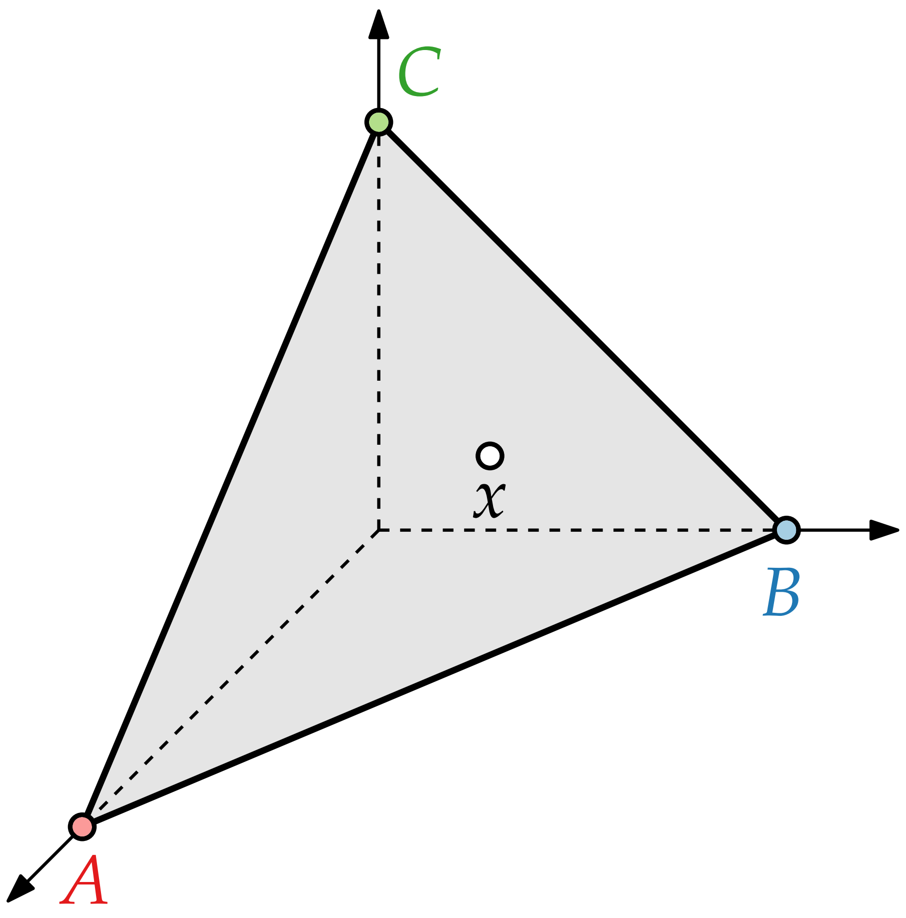

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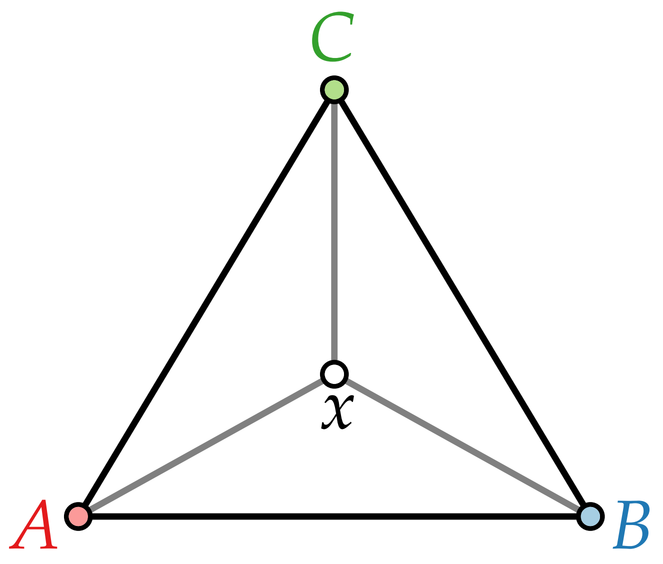

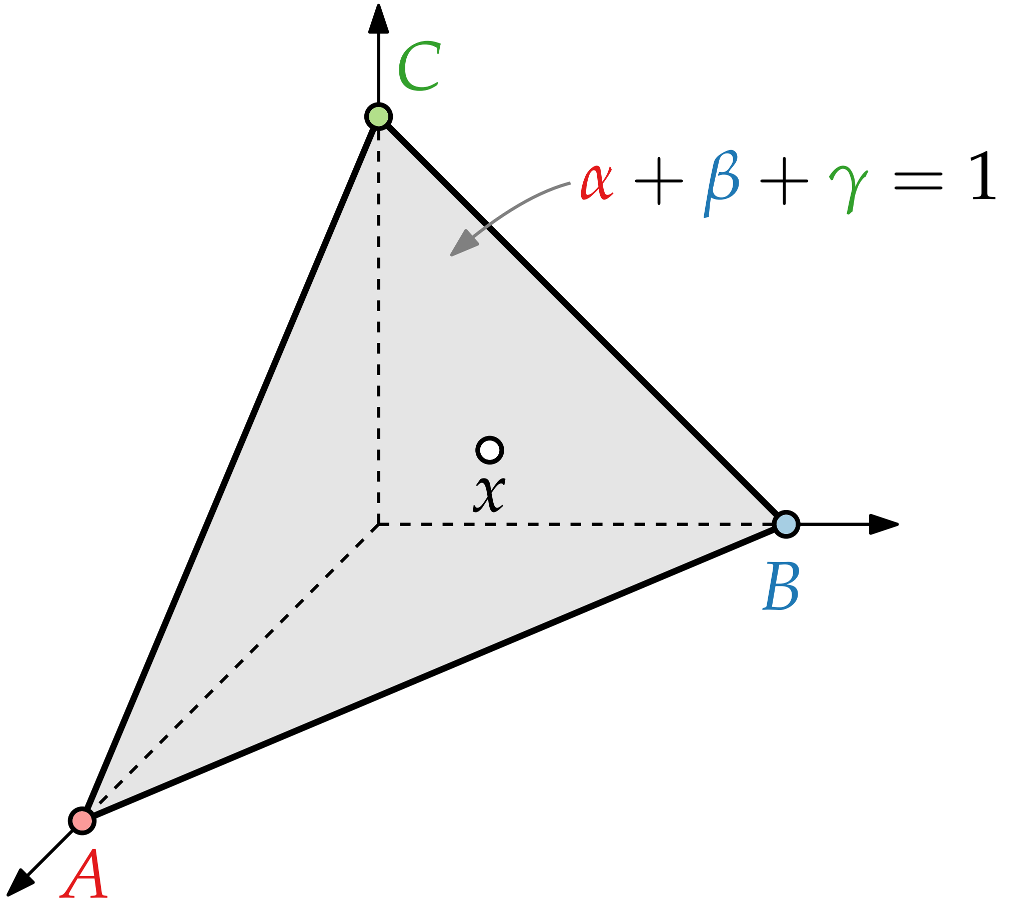

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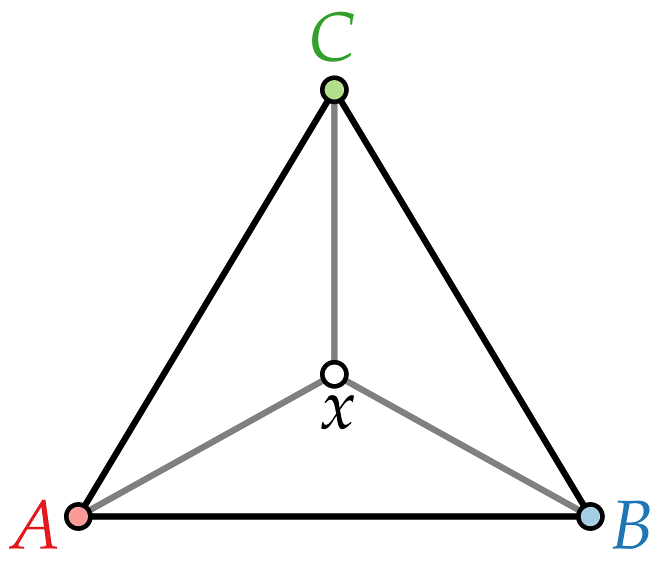

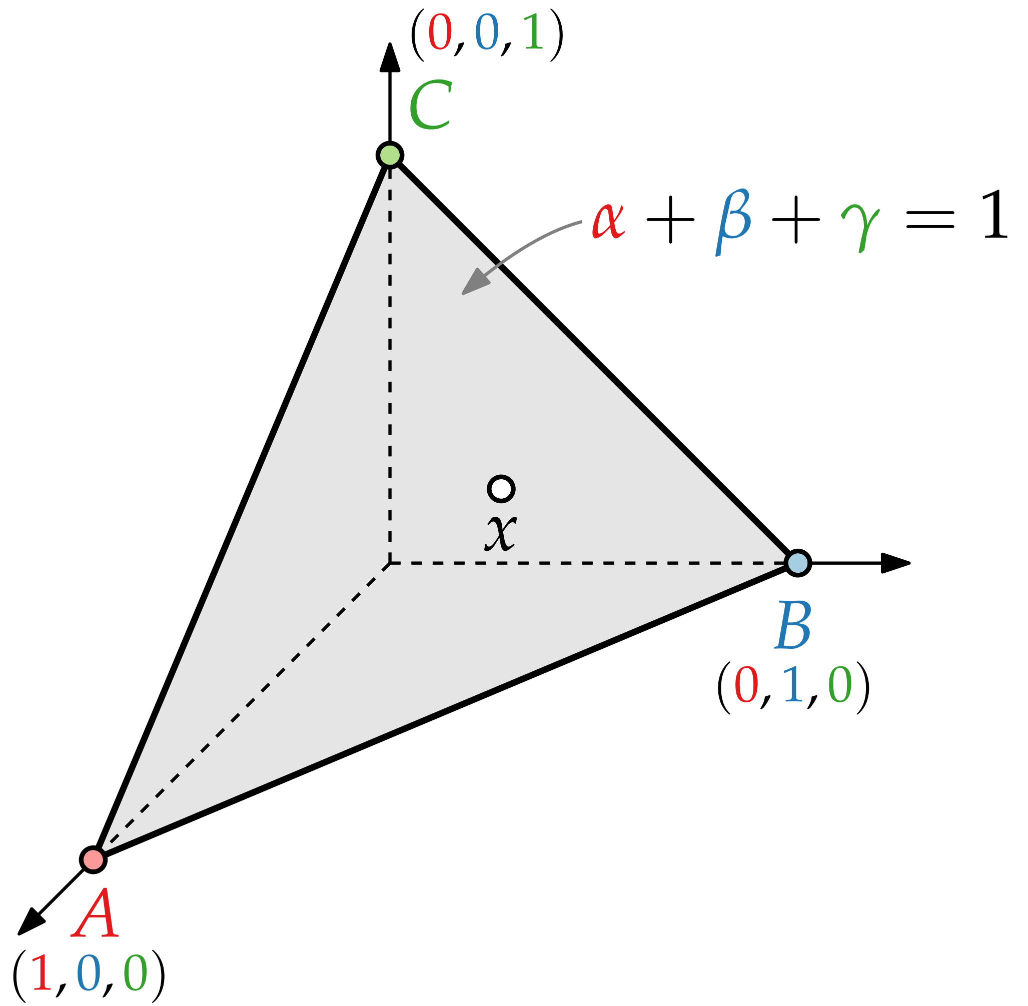

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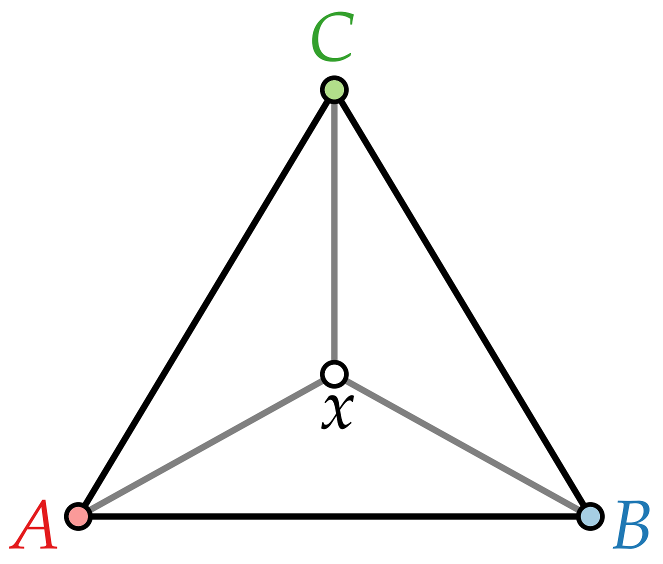

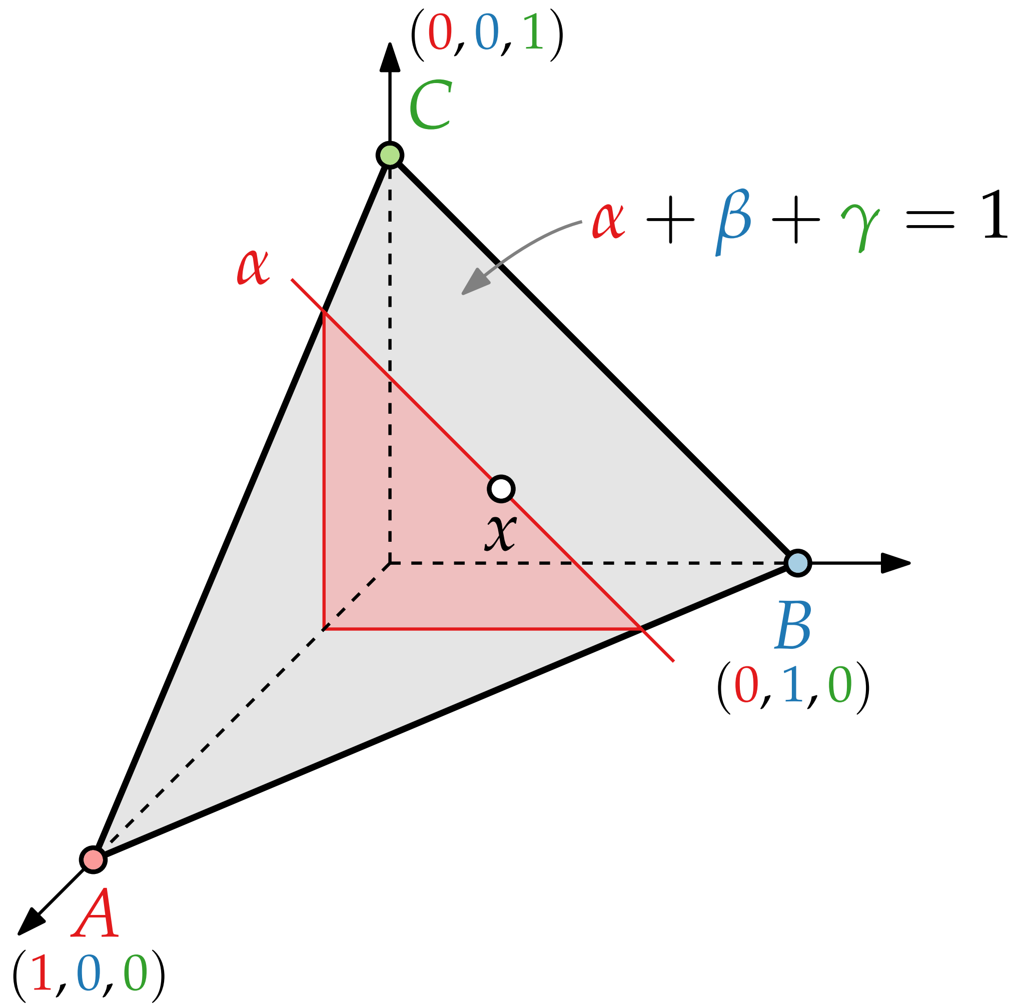

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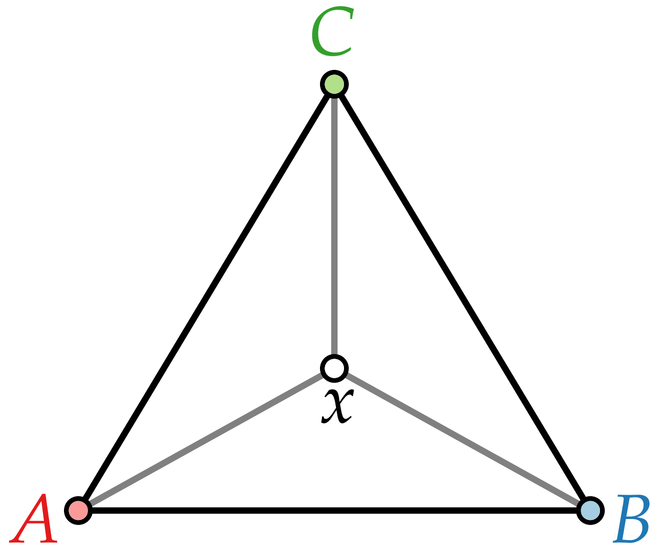

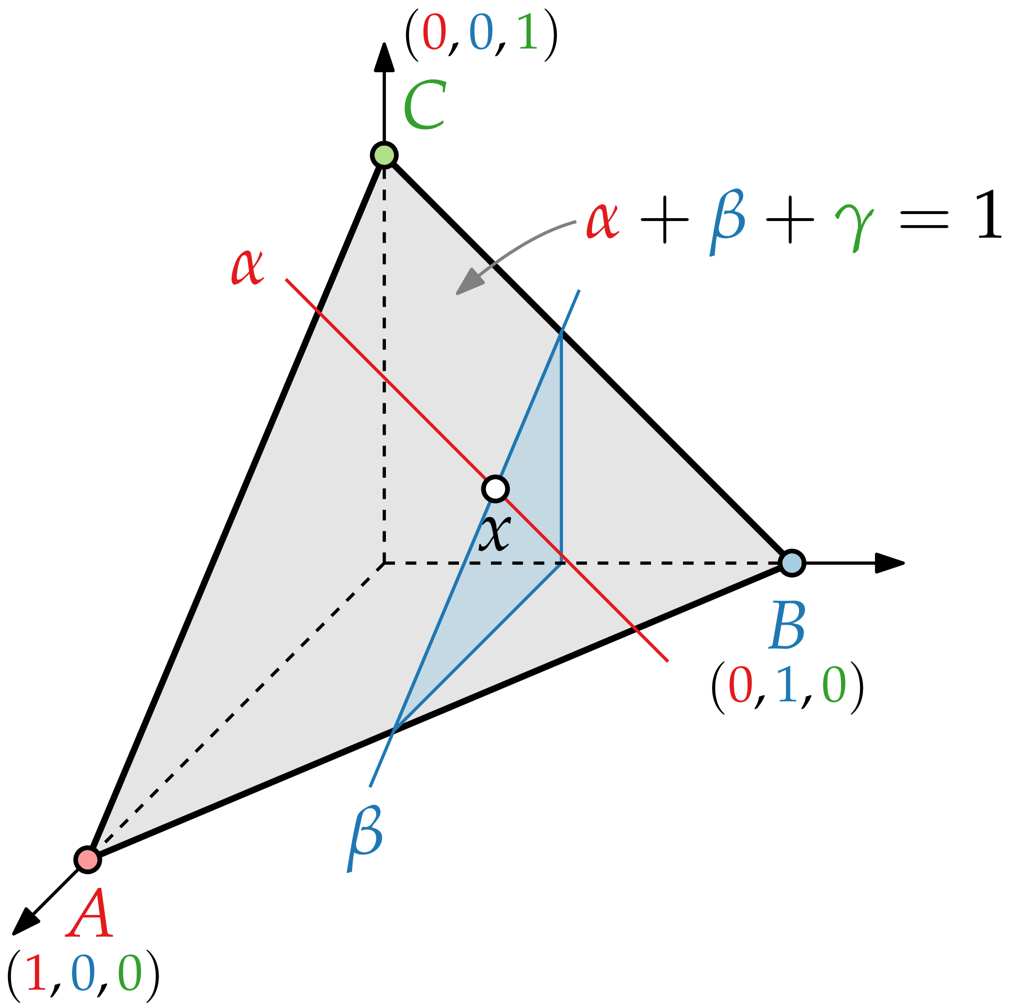

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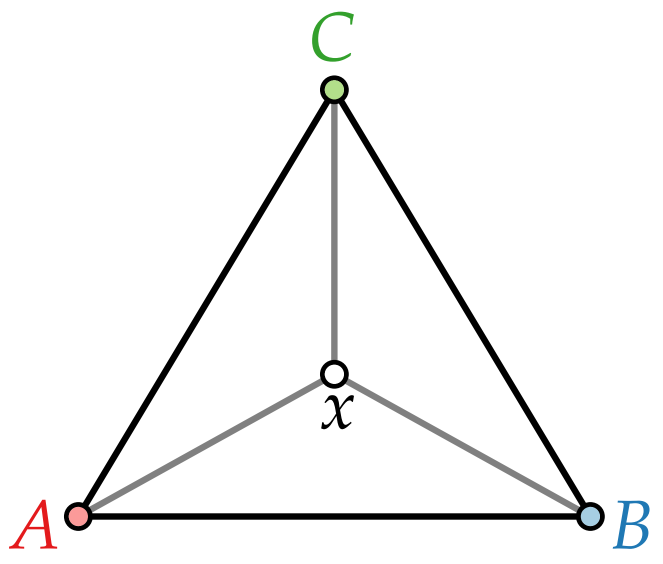

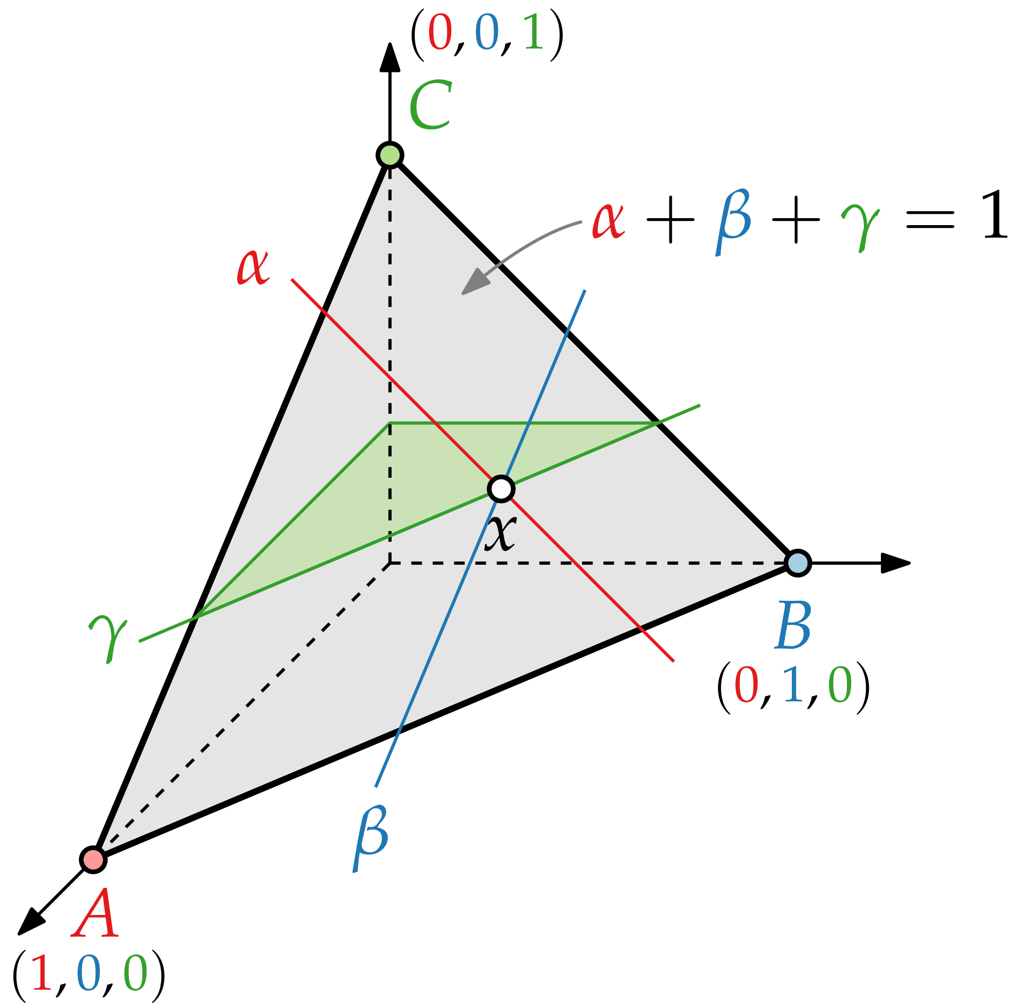

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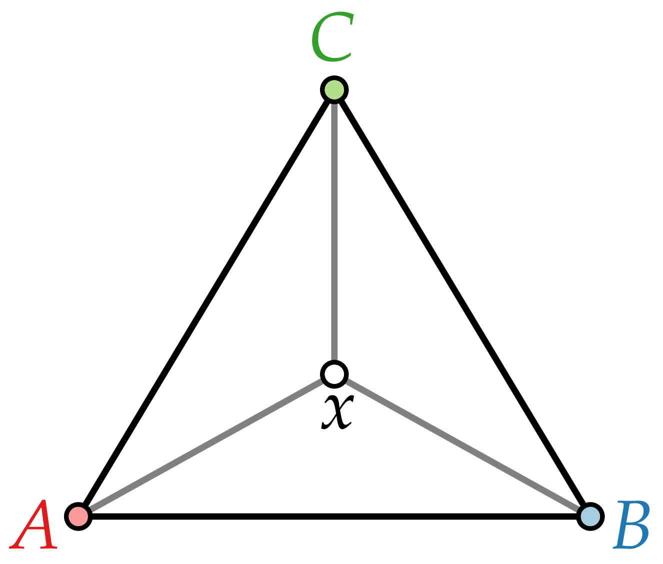

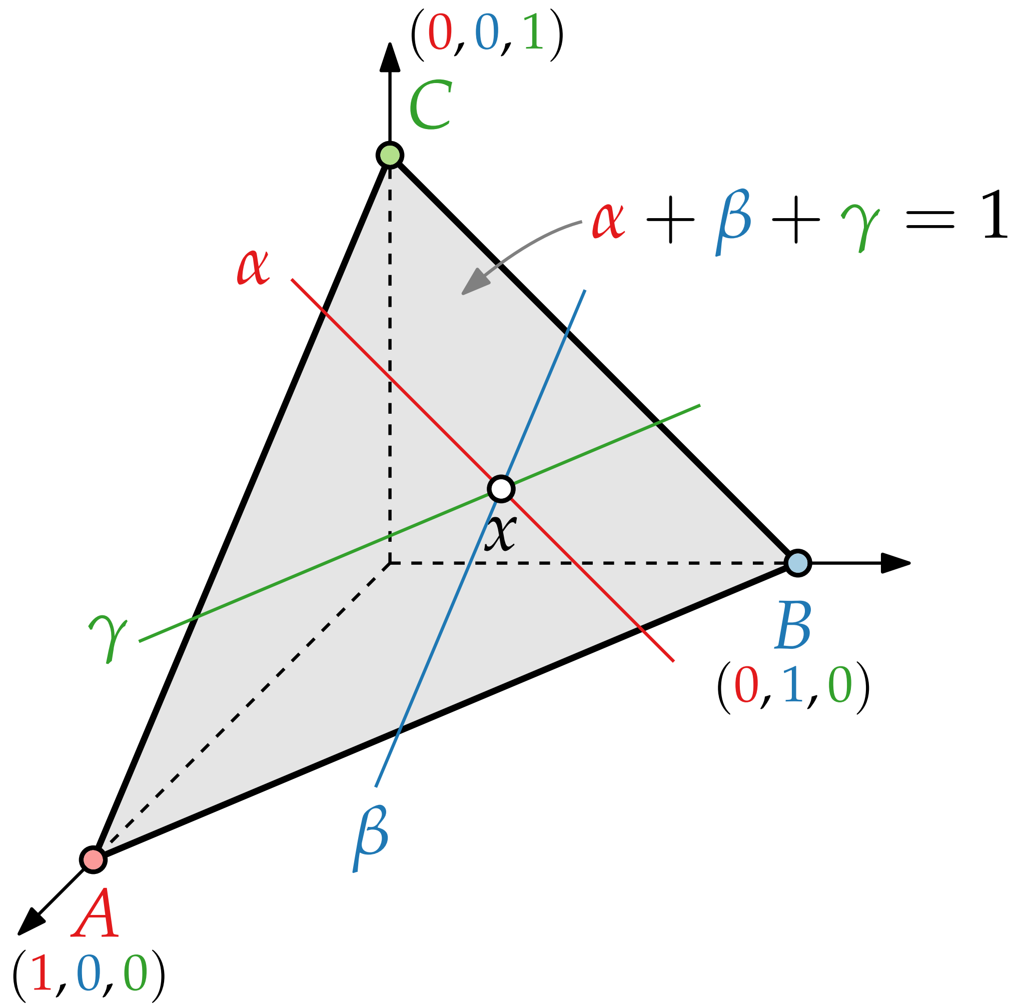

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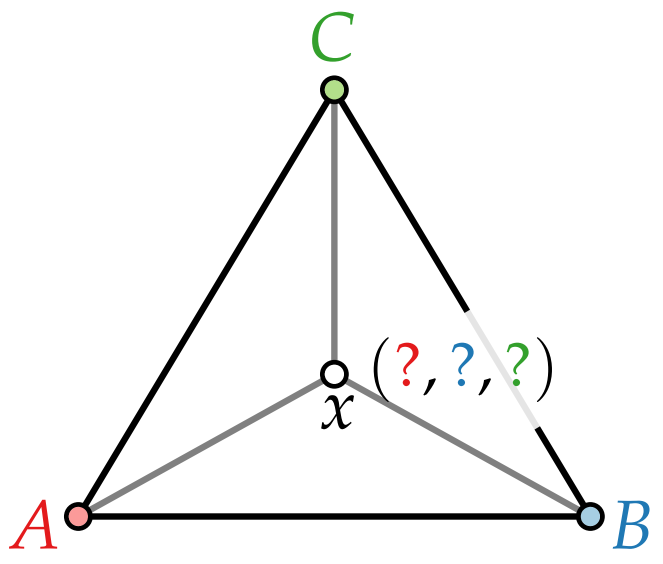

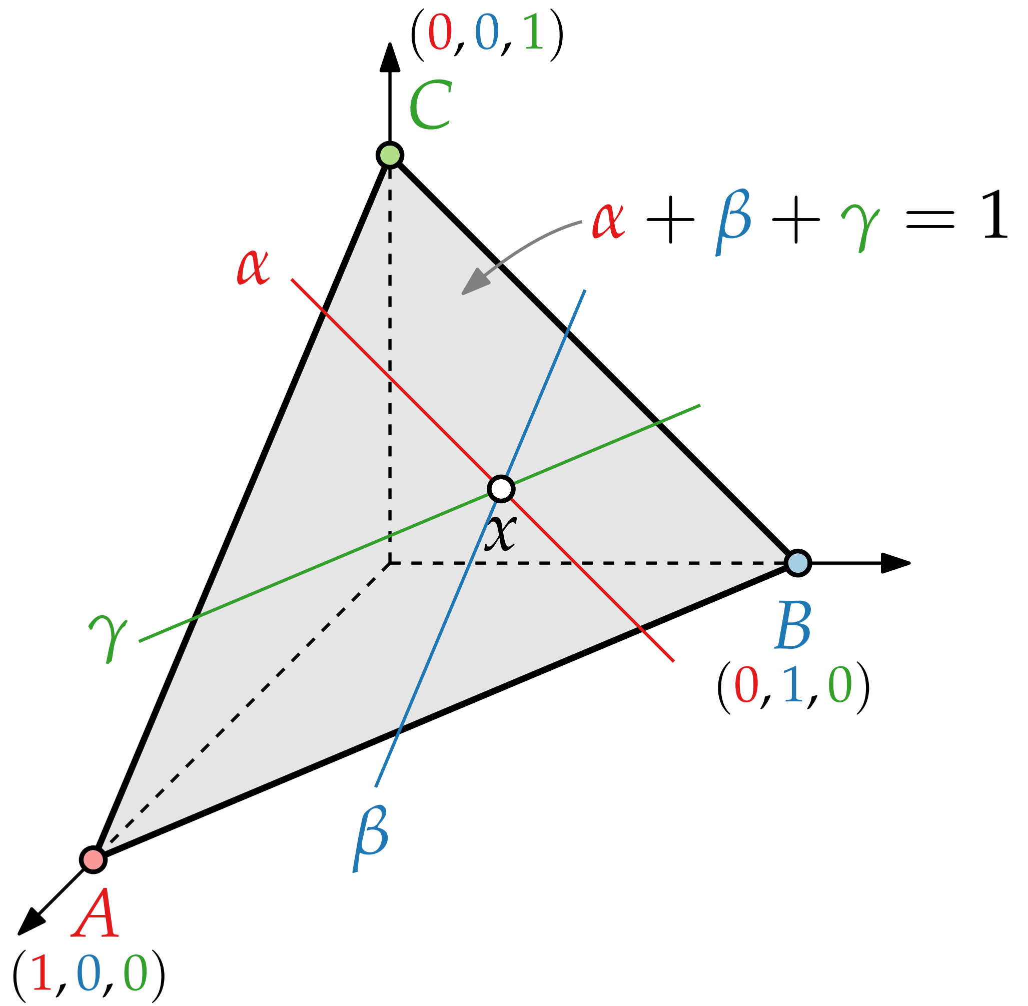

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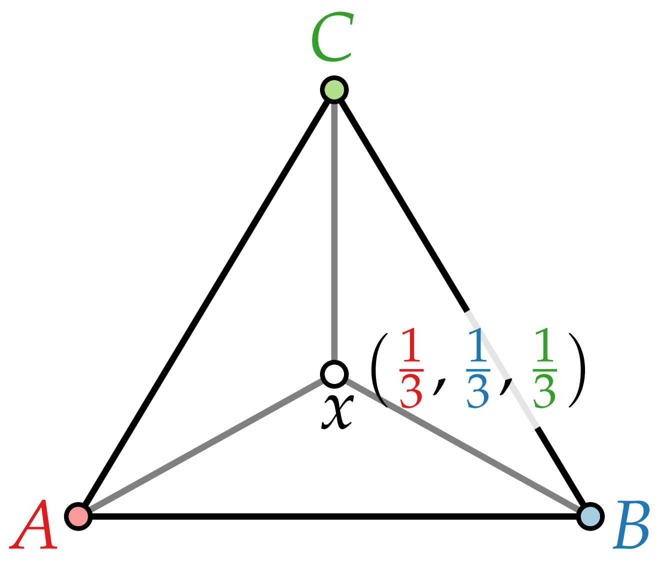

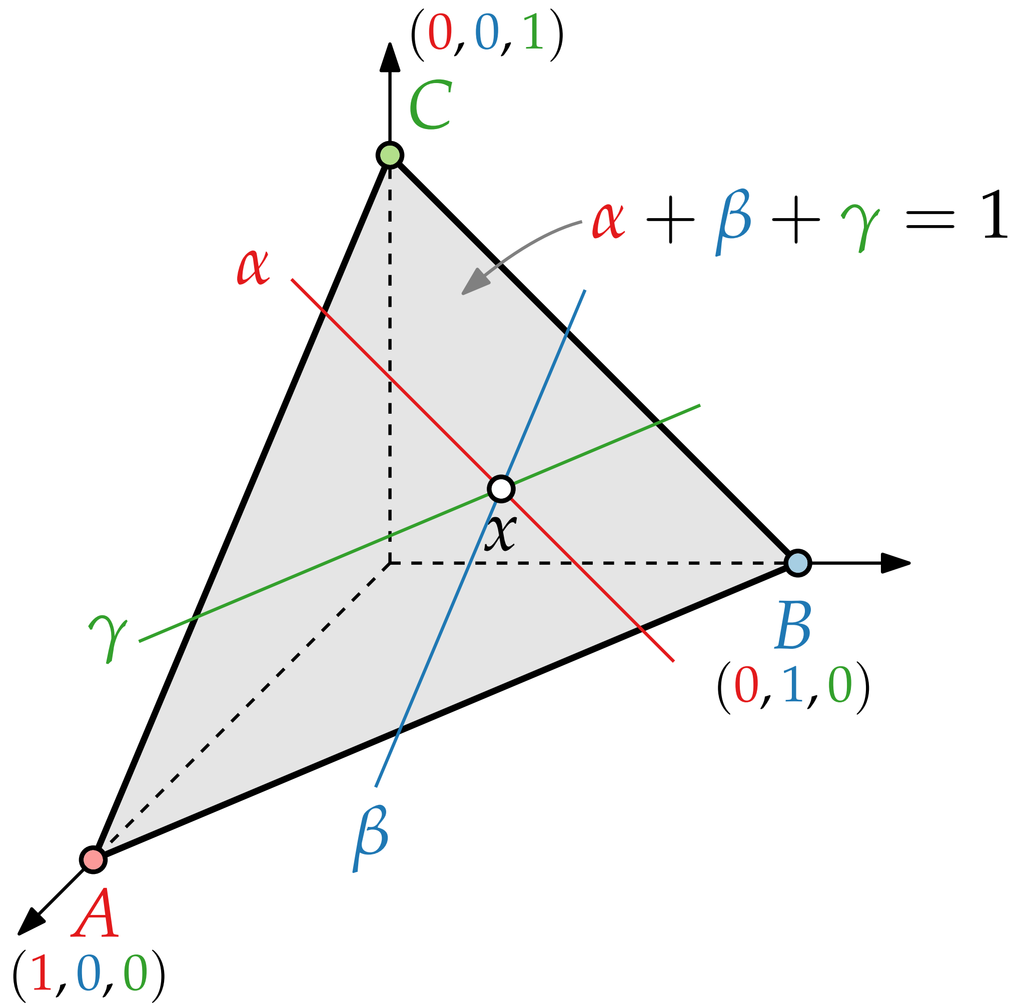

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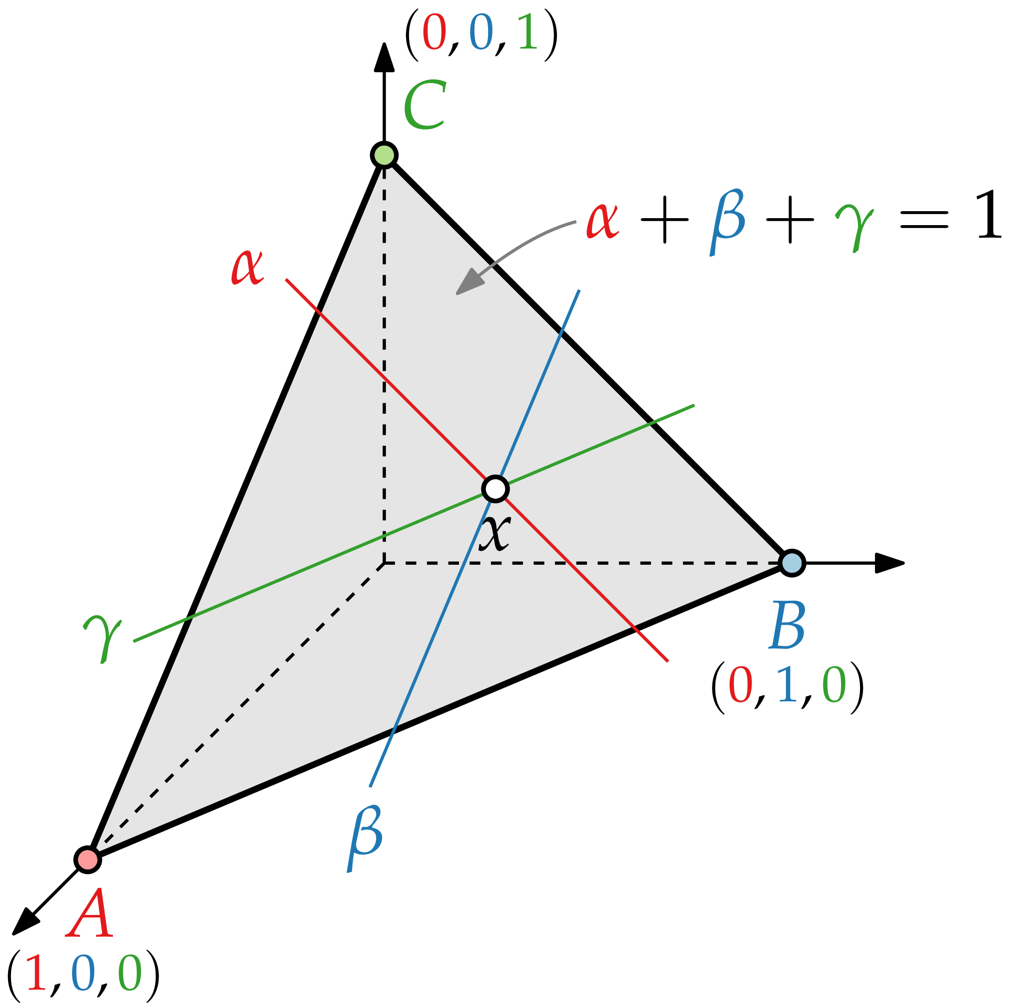

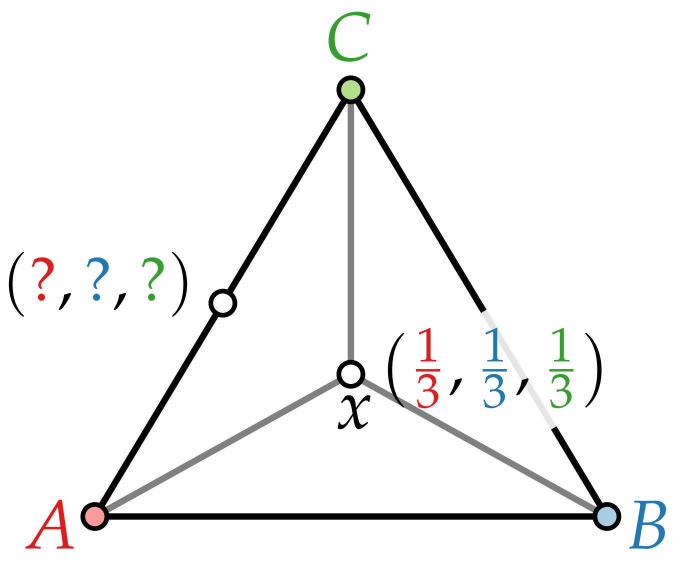

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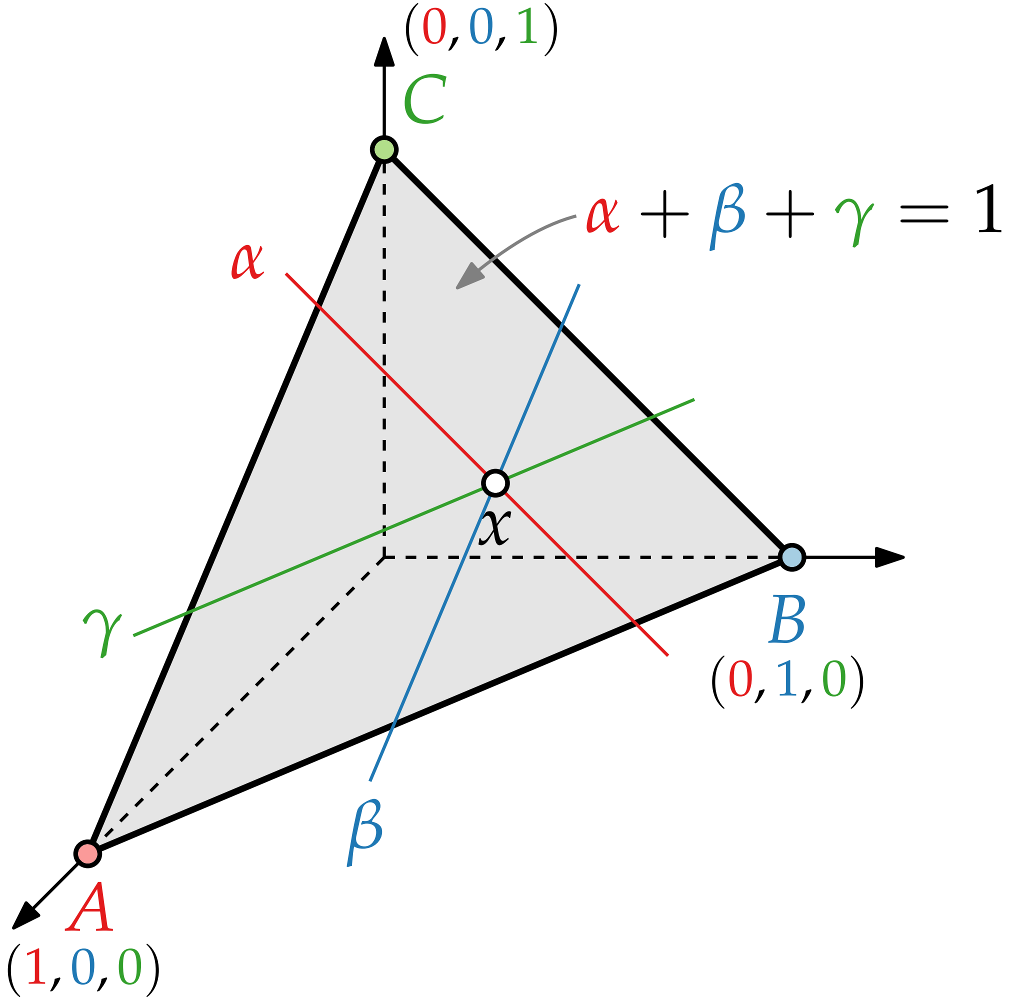
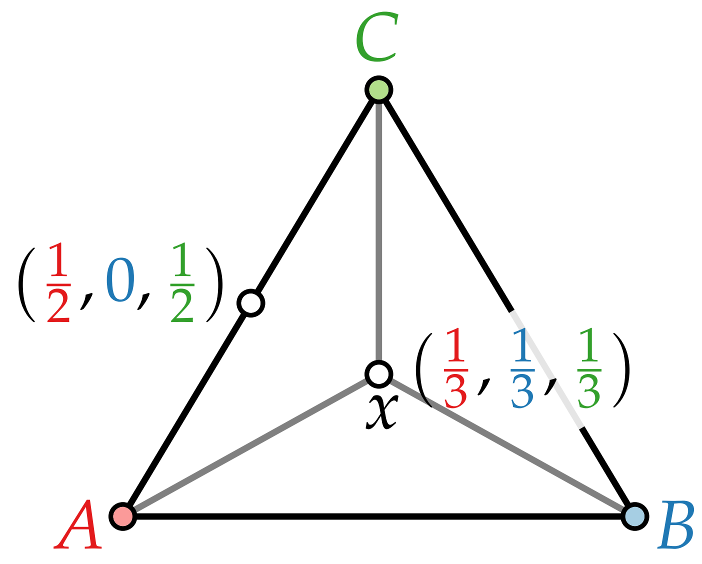


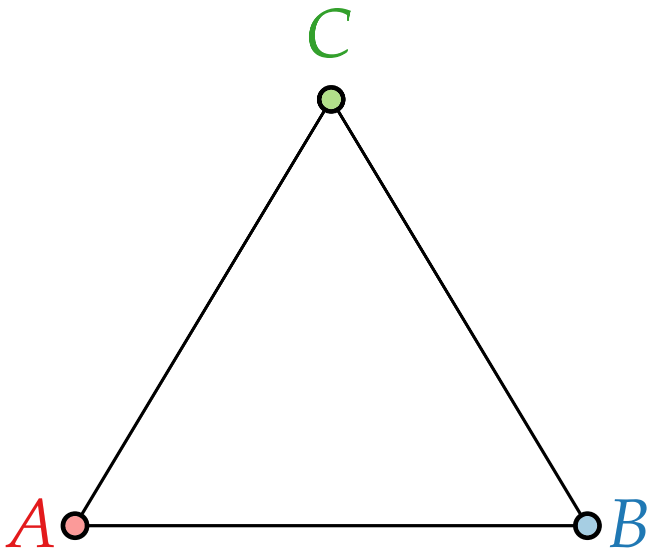


Barycentric Representation

A **barycentric representation** of a graph $G = (V, E)$ is an assignment of barycentric coordinates to the vertices of G:

$$f \colon V \to \mathbb{R}^3_{\geq 0}, v \mapsto (v_1, v_2, v_3)$$

with the following properties:



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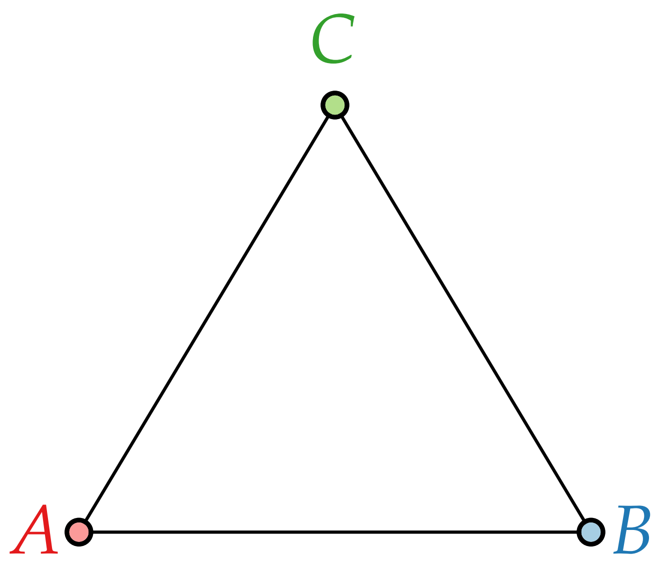
(B1) $v_1 + v_2 + v_3 = 1$ for all $v \in V$,



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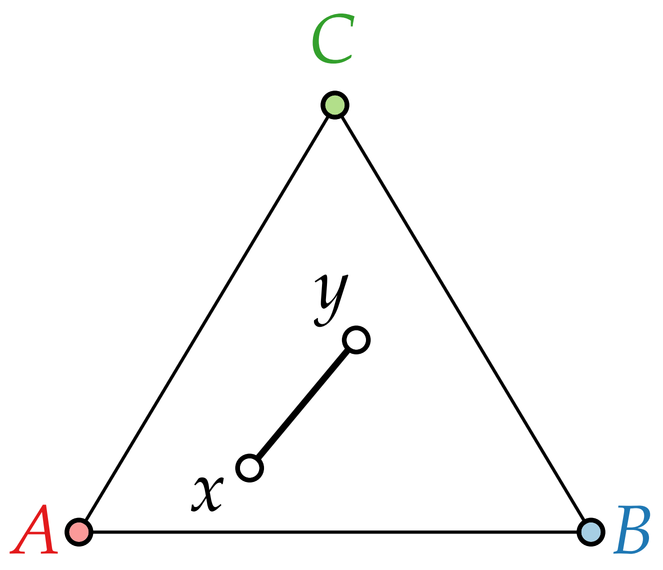

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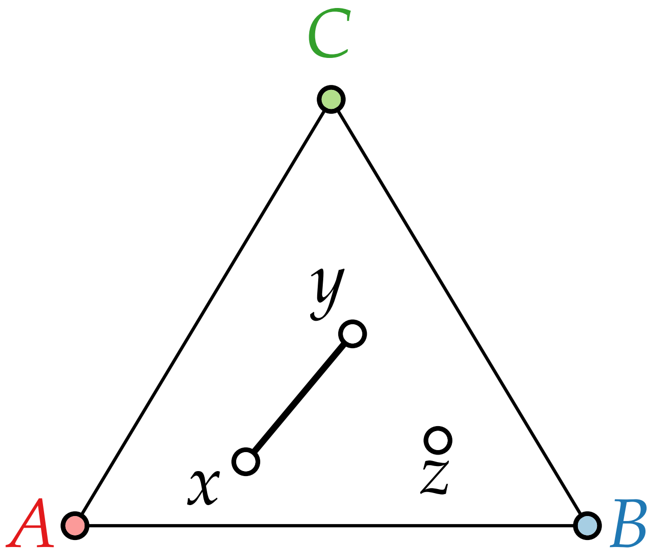

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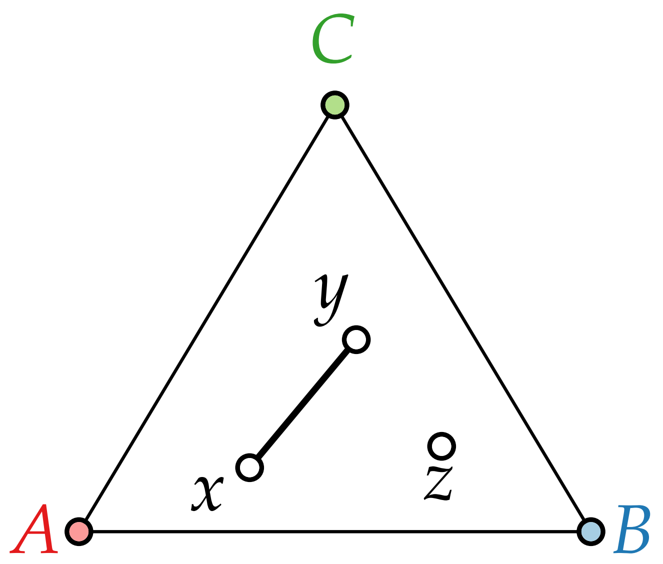

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A **barycentric representation** of a graph $G = (V, E)$ is an assignment of barycentric coordinates to the vertices of G:

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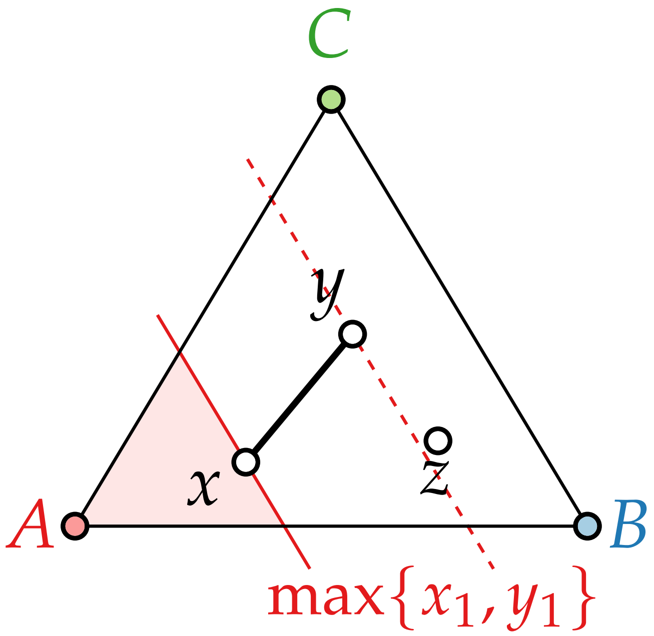

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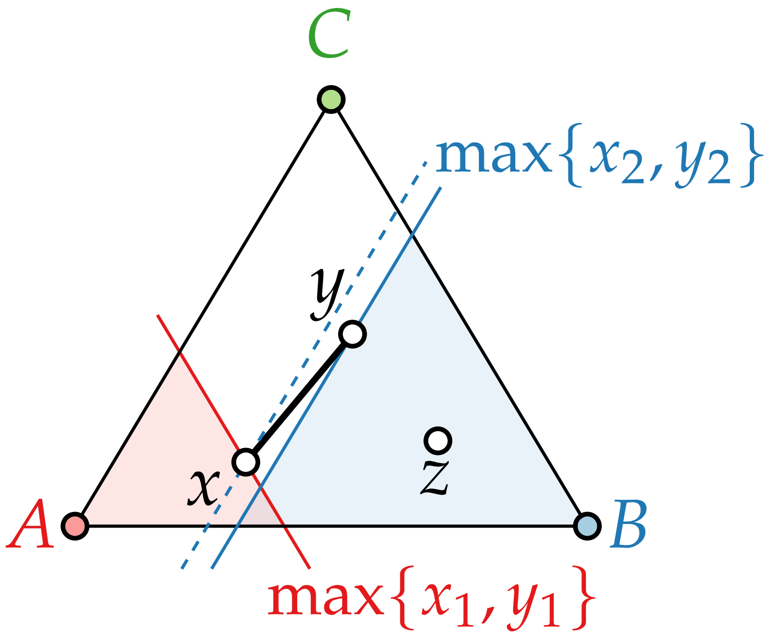

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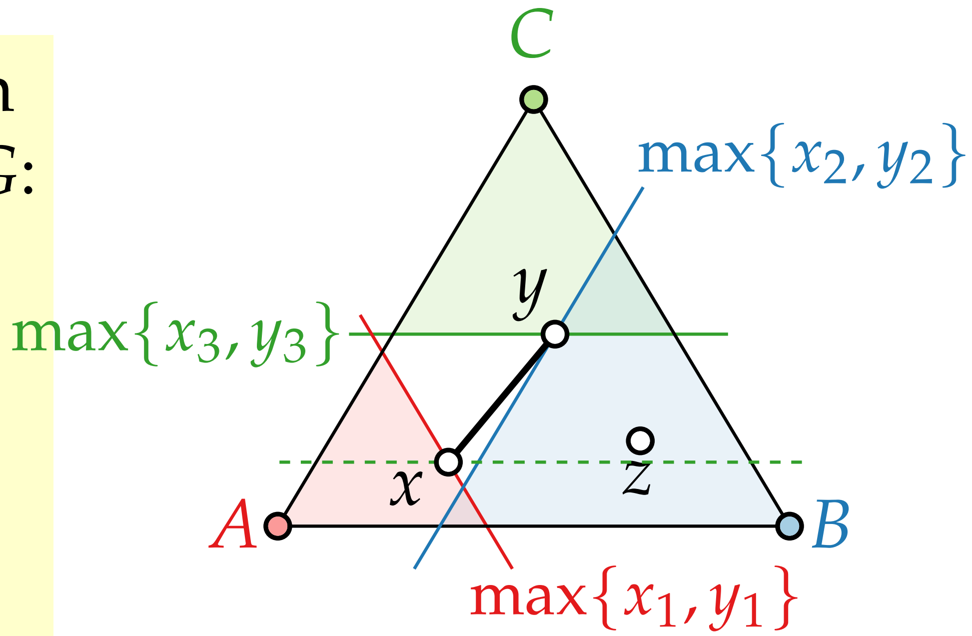

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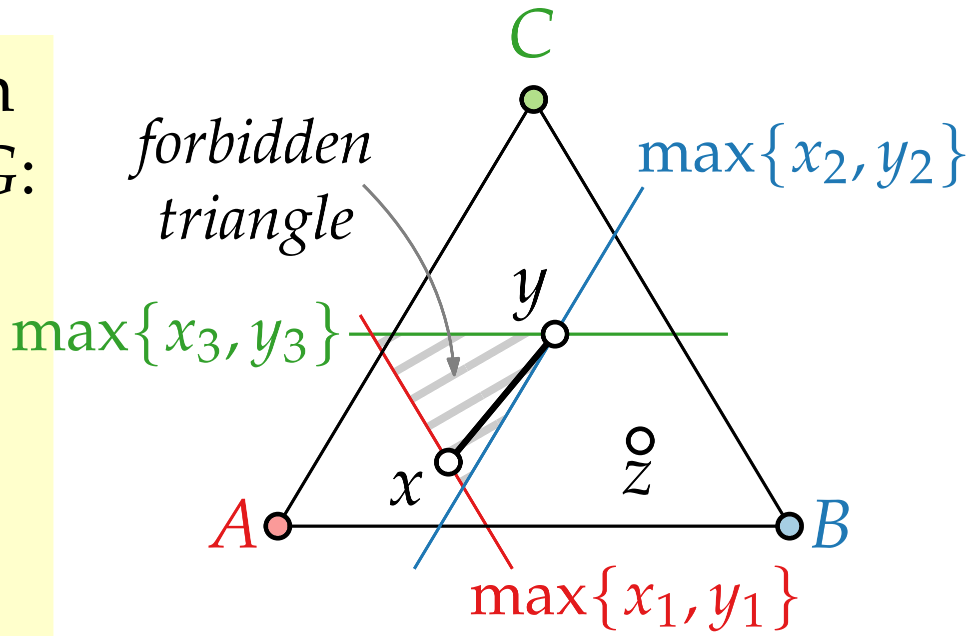

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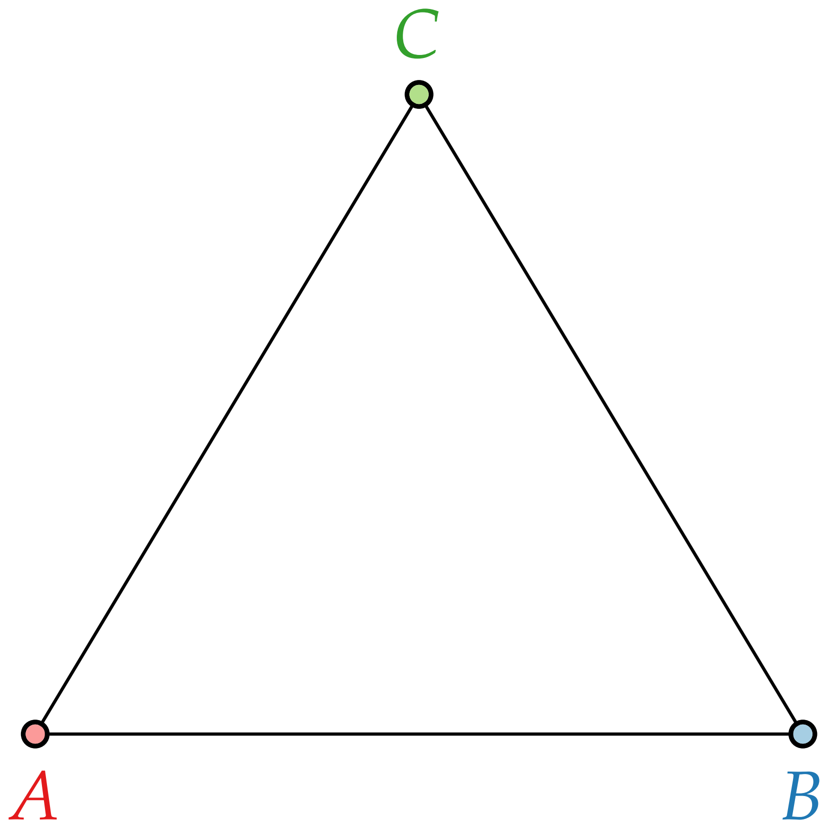

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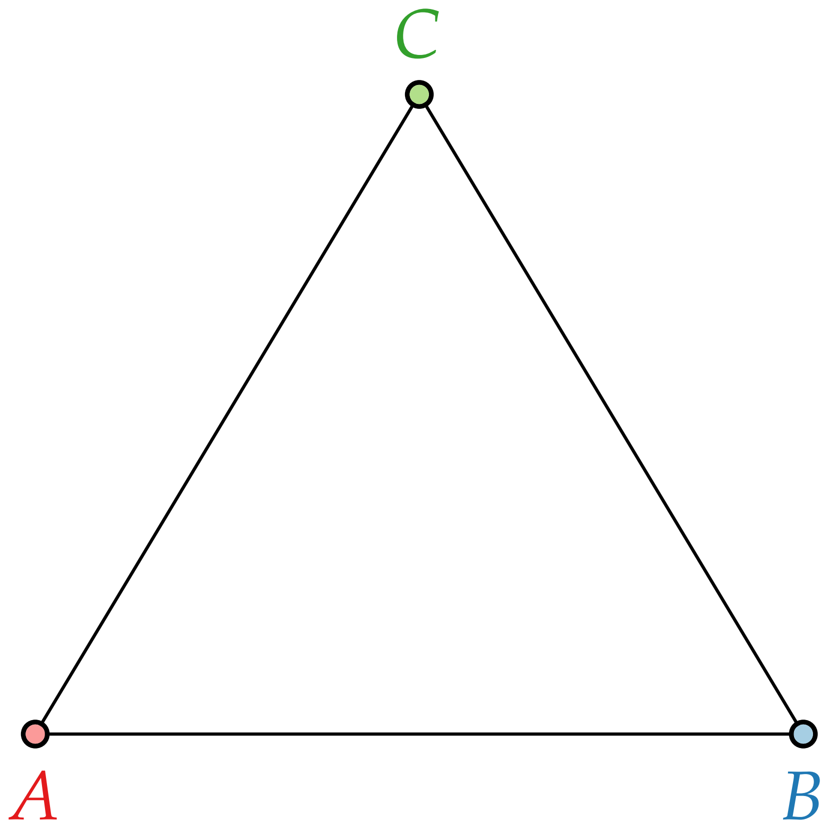

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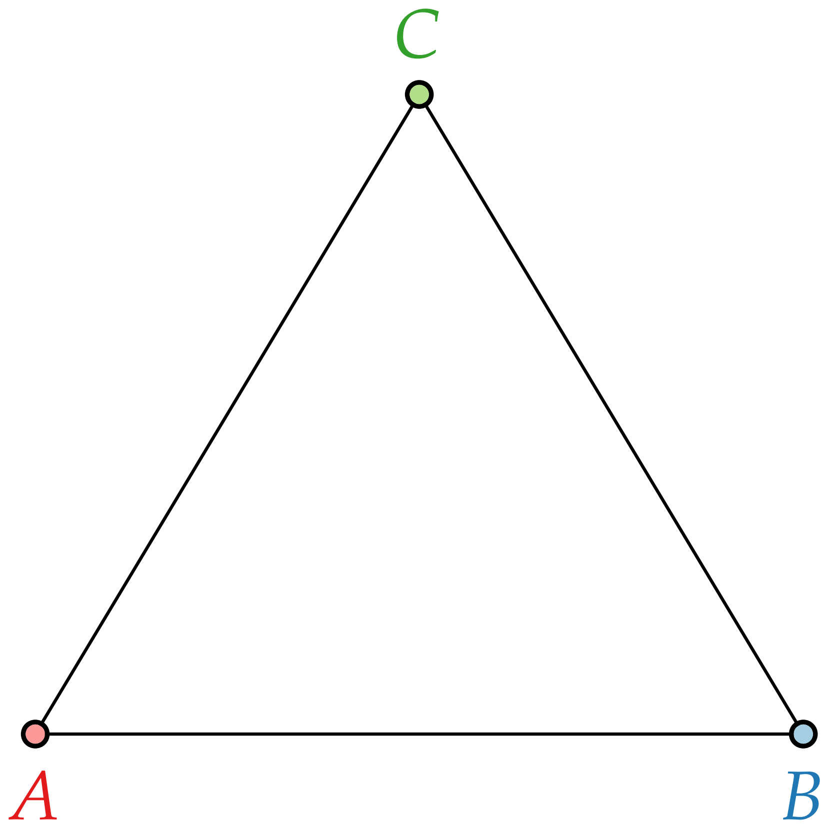

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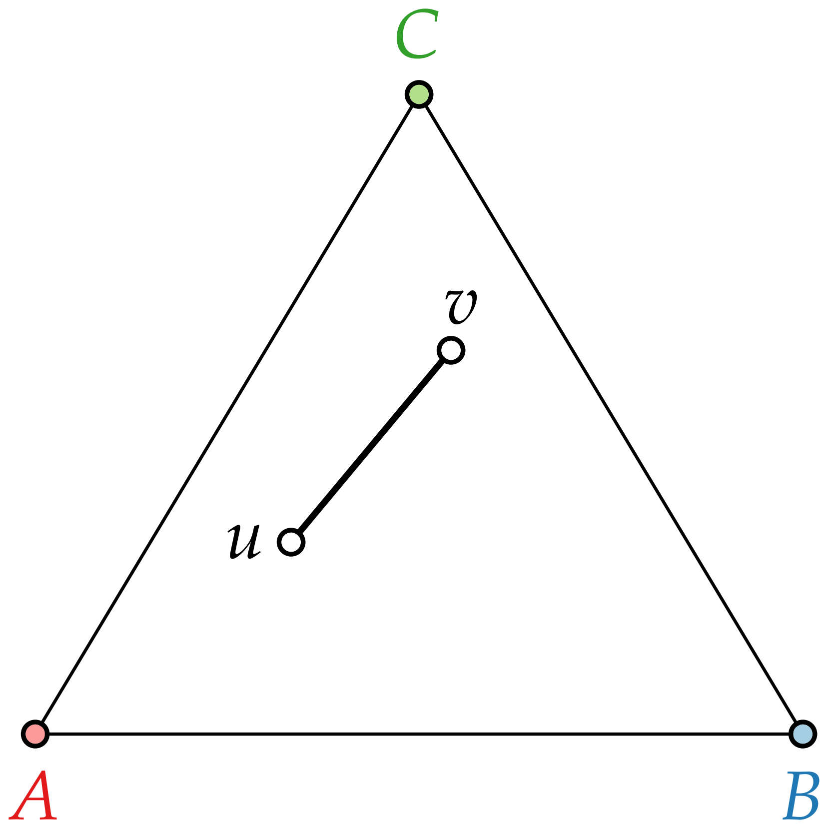

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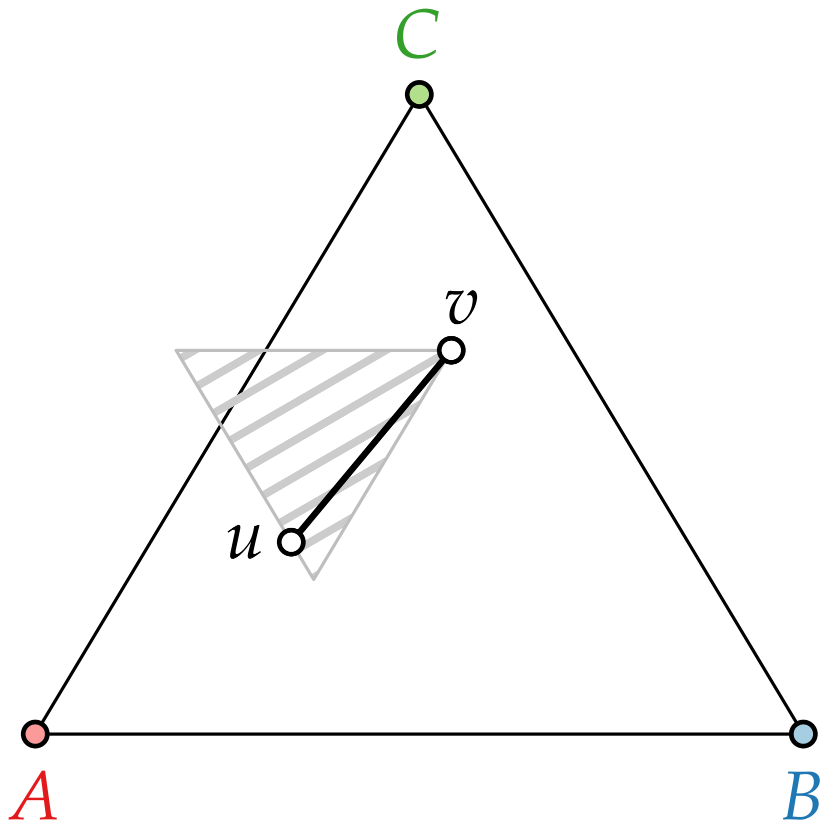

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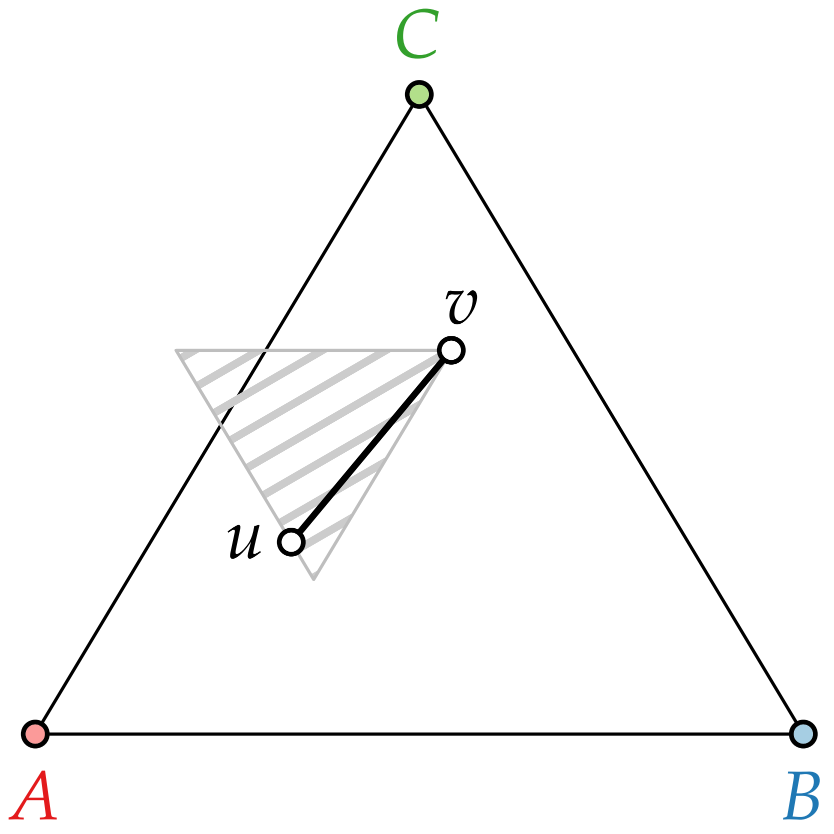

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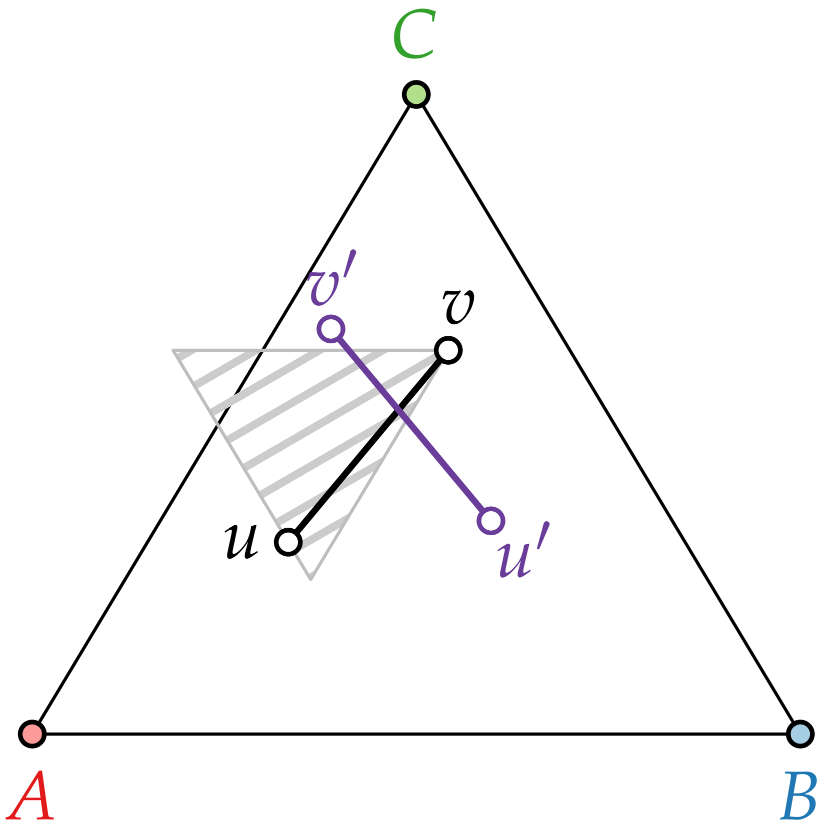

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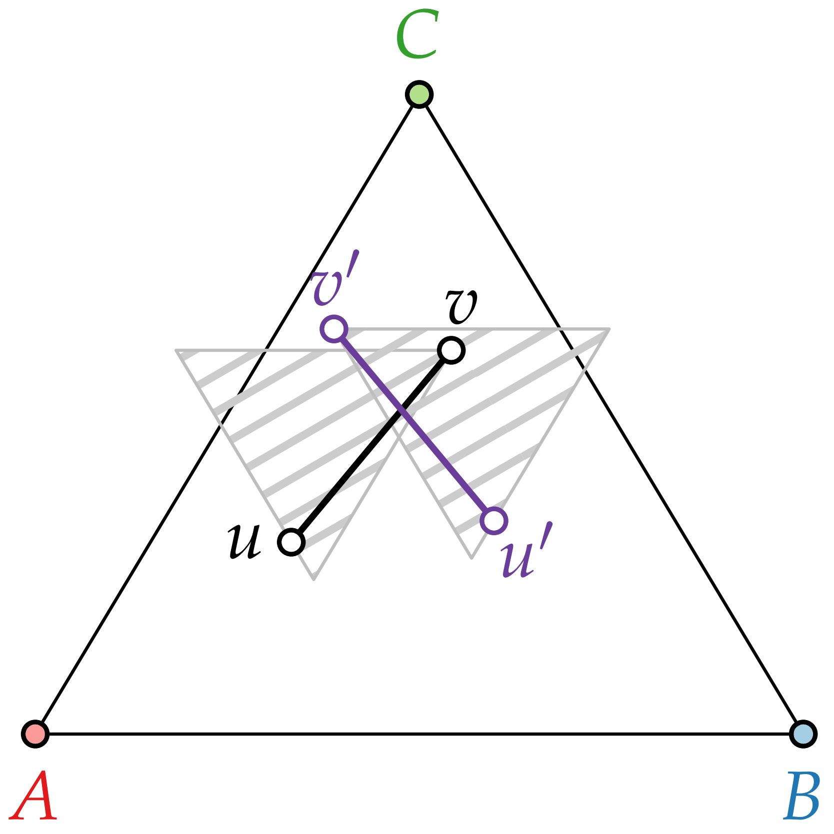

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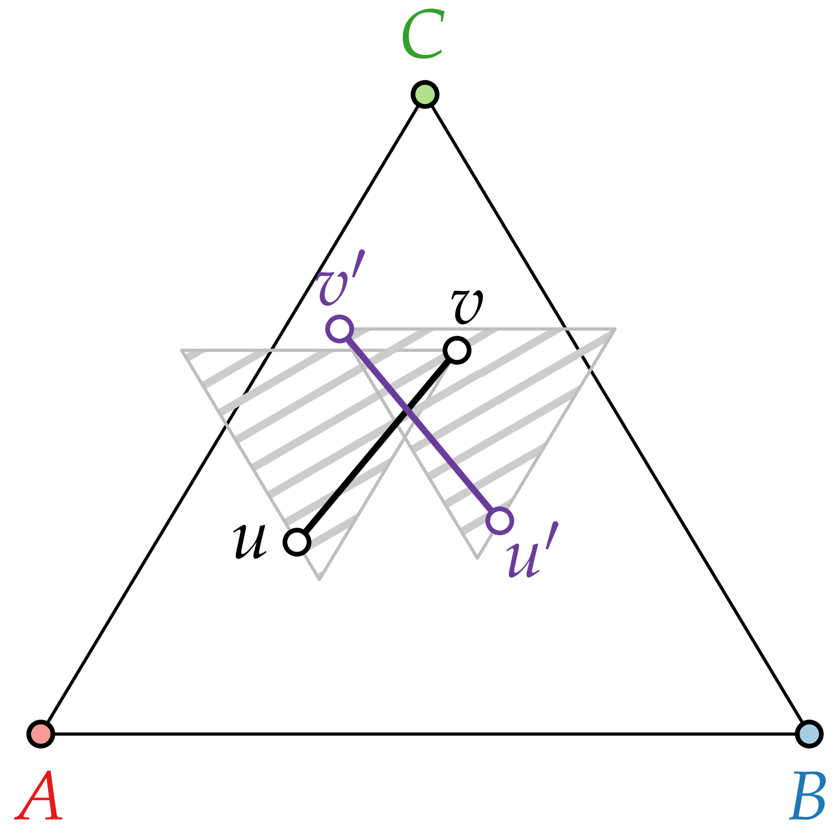

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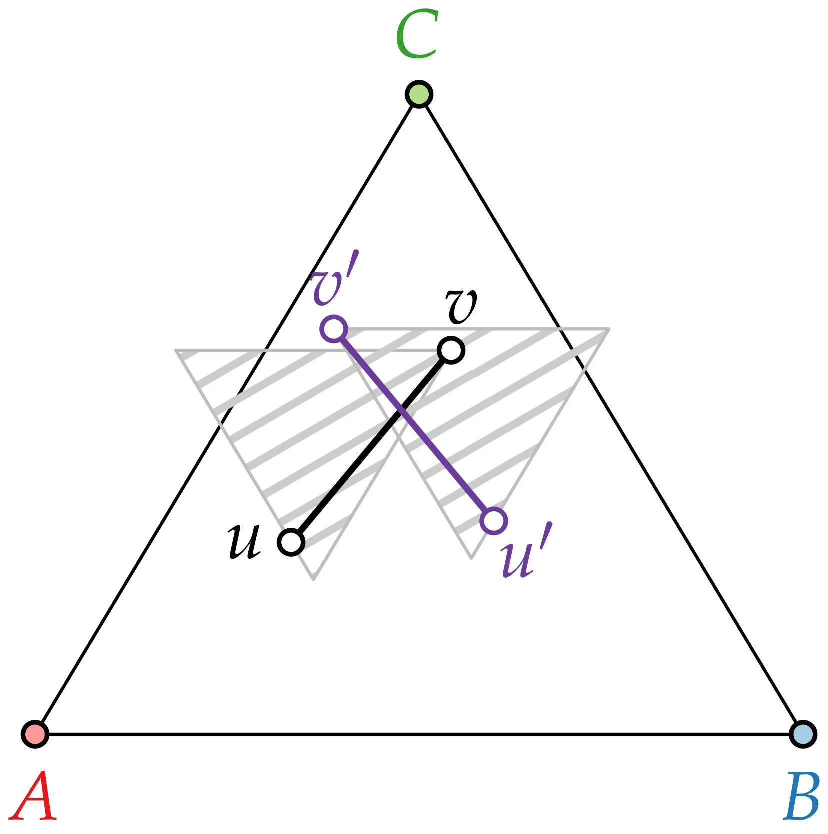

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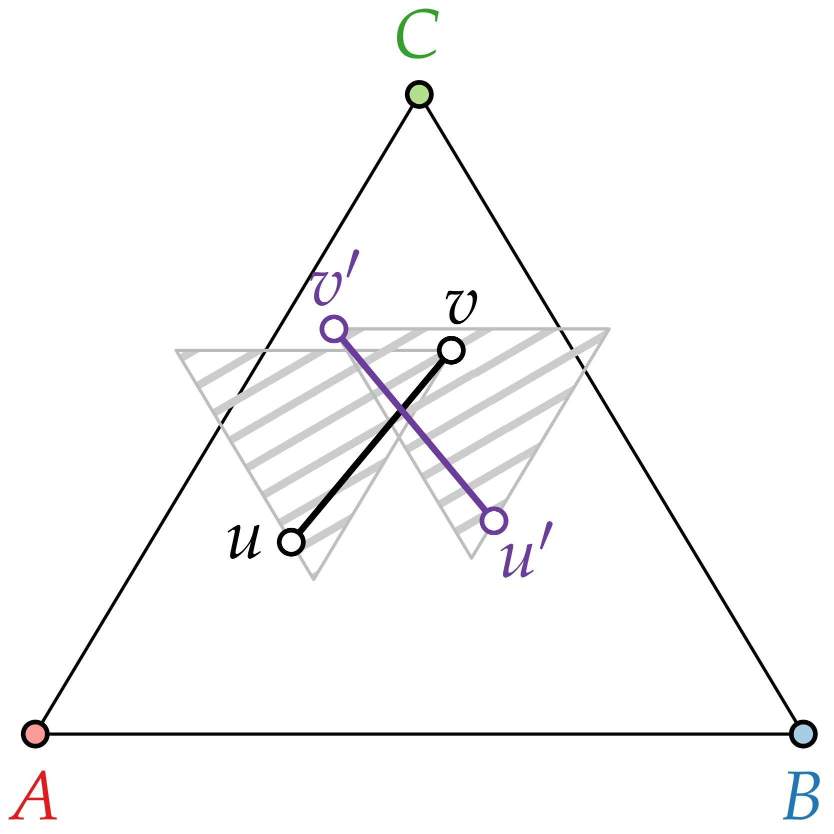

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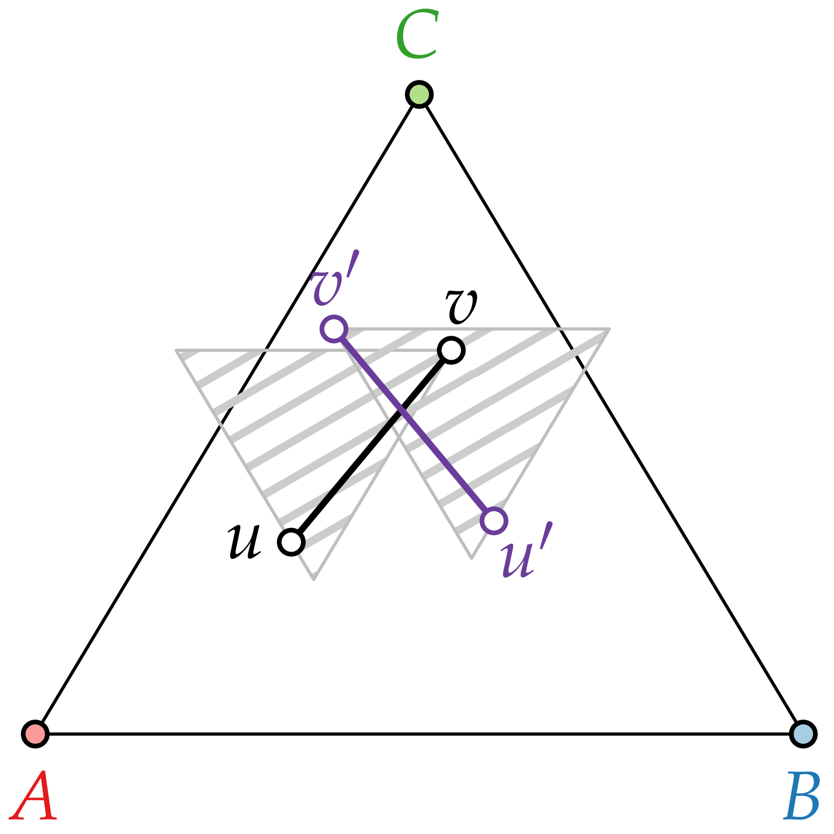

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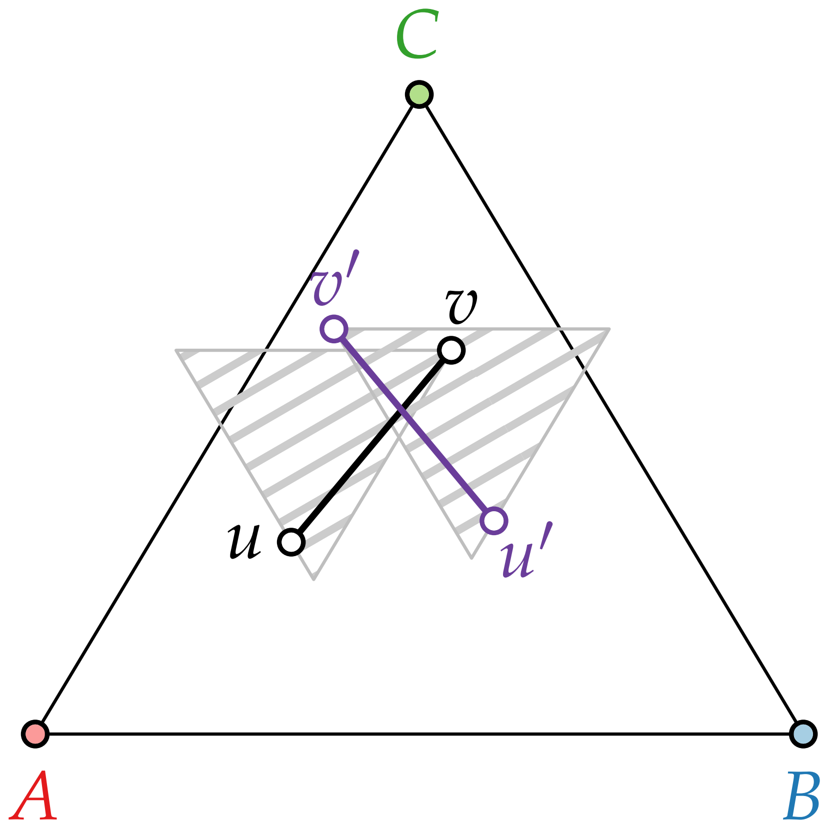

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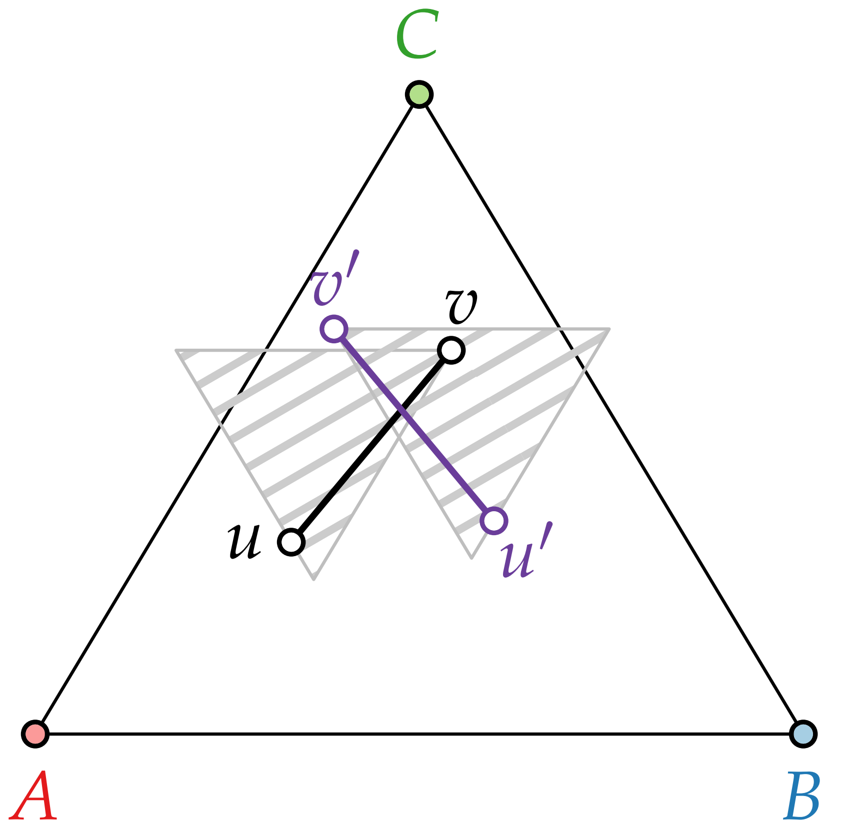

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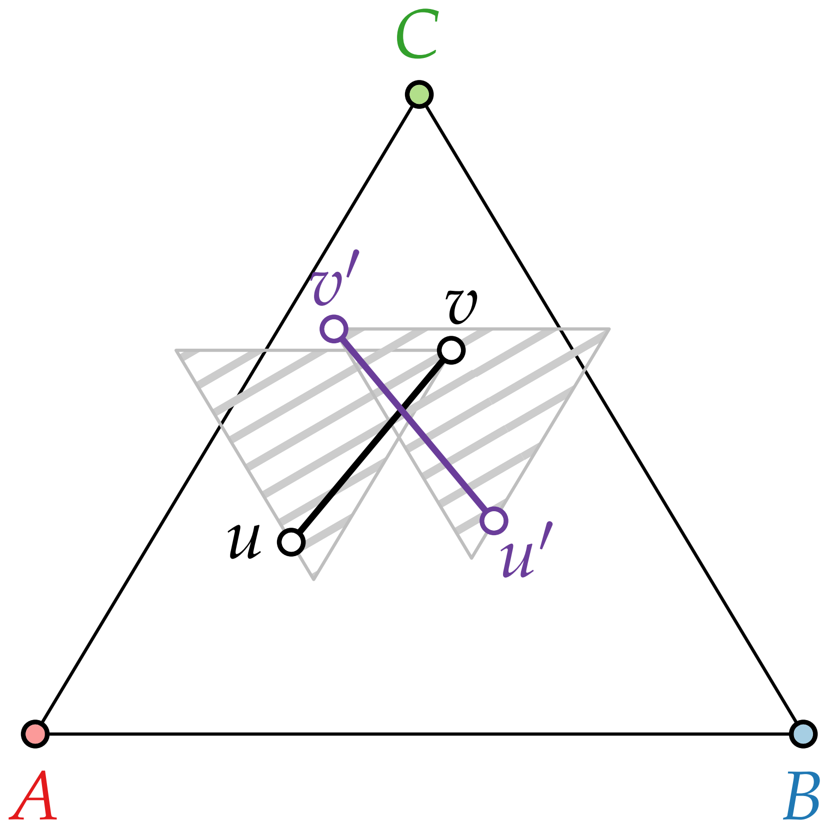

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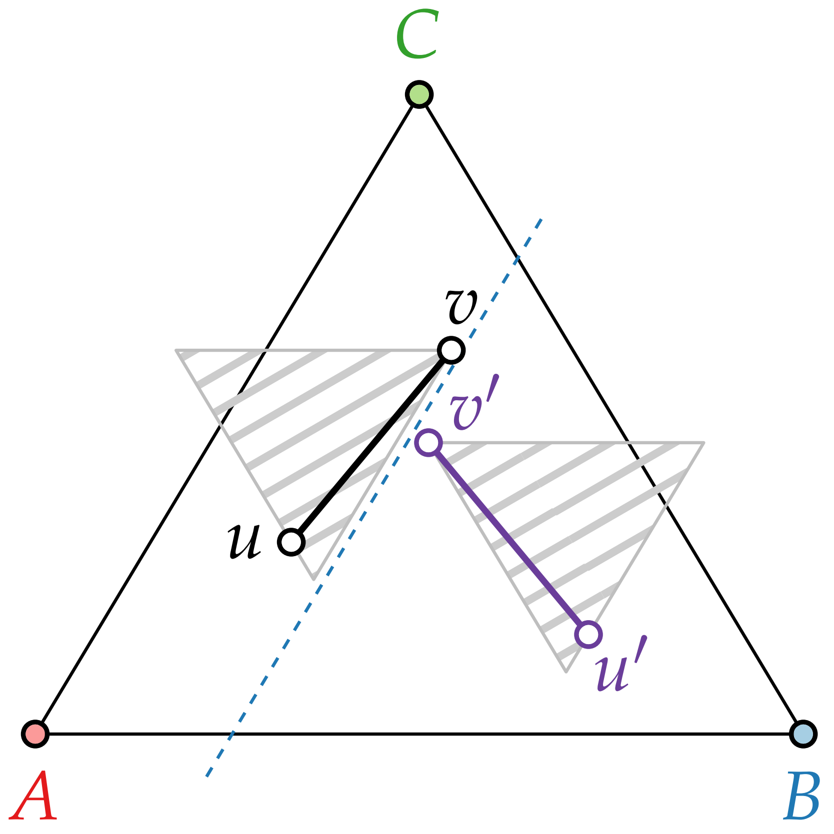

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Barycentric Representations of Planar Graphs

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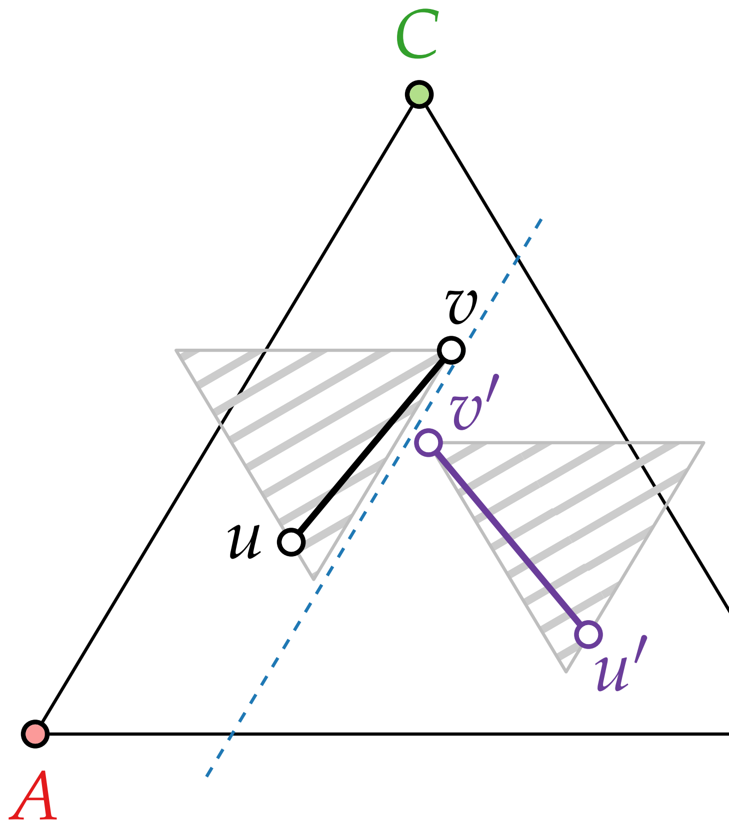

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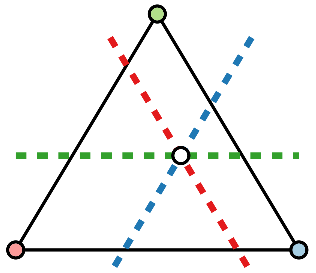
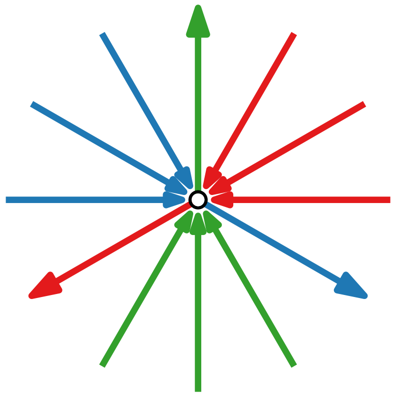
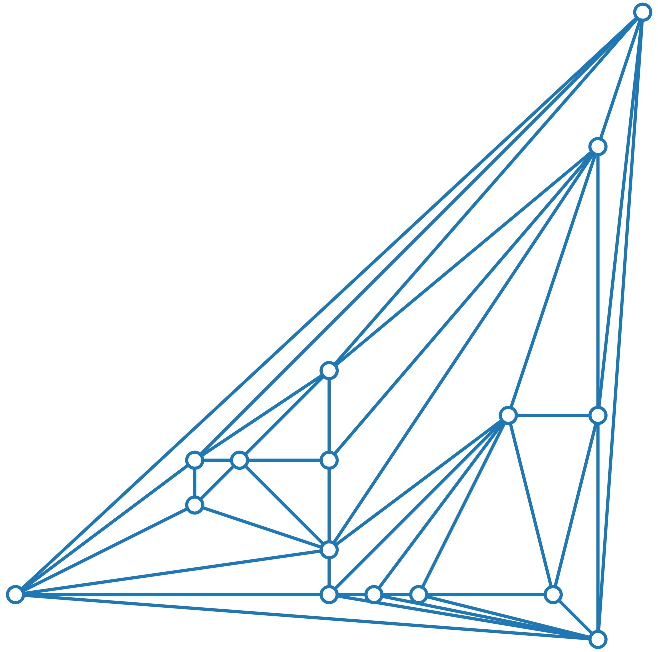
Universität Trier



Visualization of Graphs



Lecture 5:
Straight-Line Drawings of Planar Graphs II: Schnyder Realizer



Part II:
Schnyder Realizer

Philipp Kindermann

Schnyder Labeling

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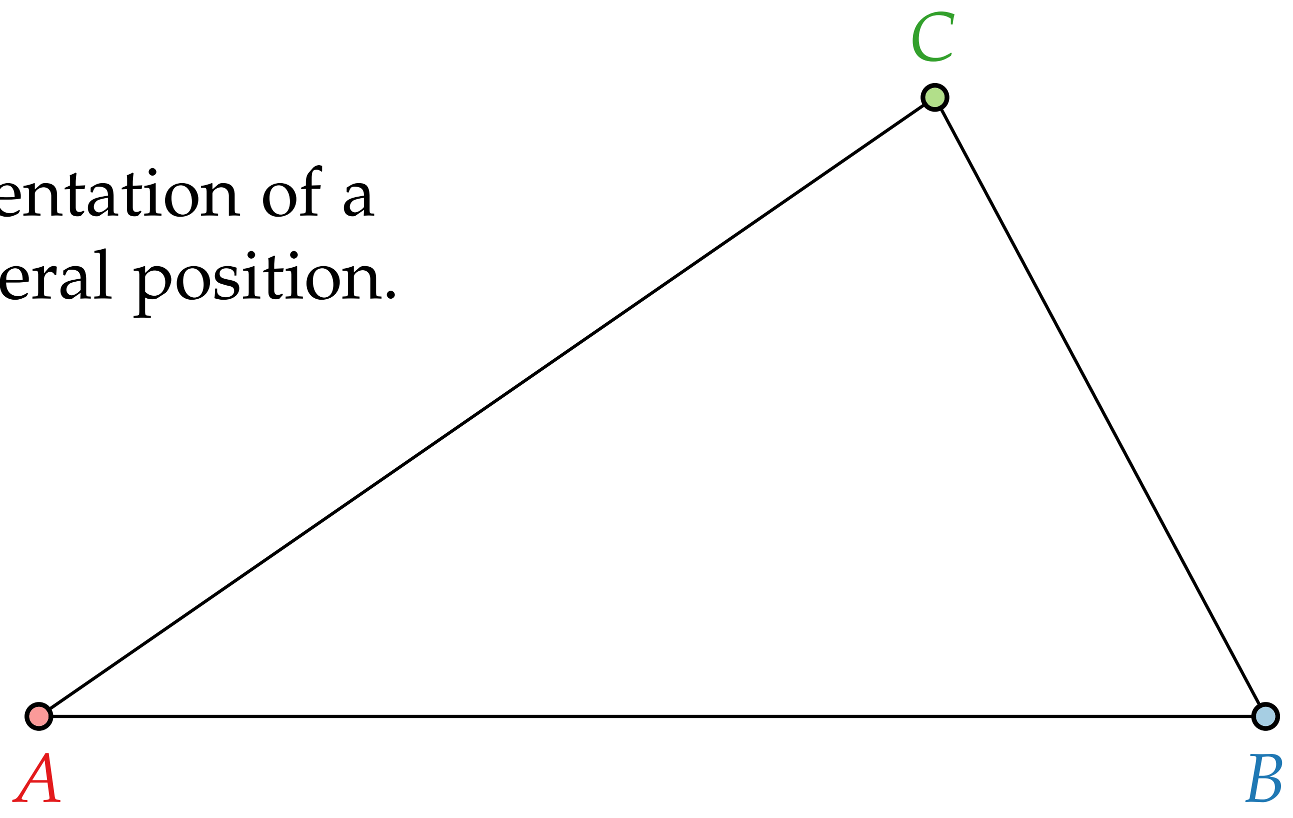

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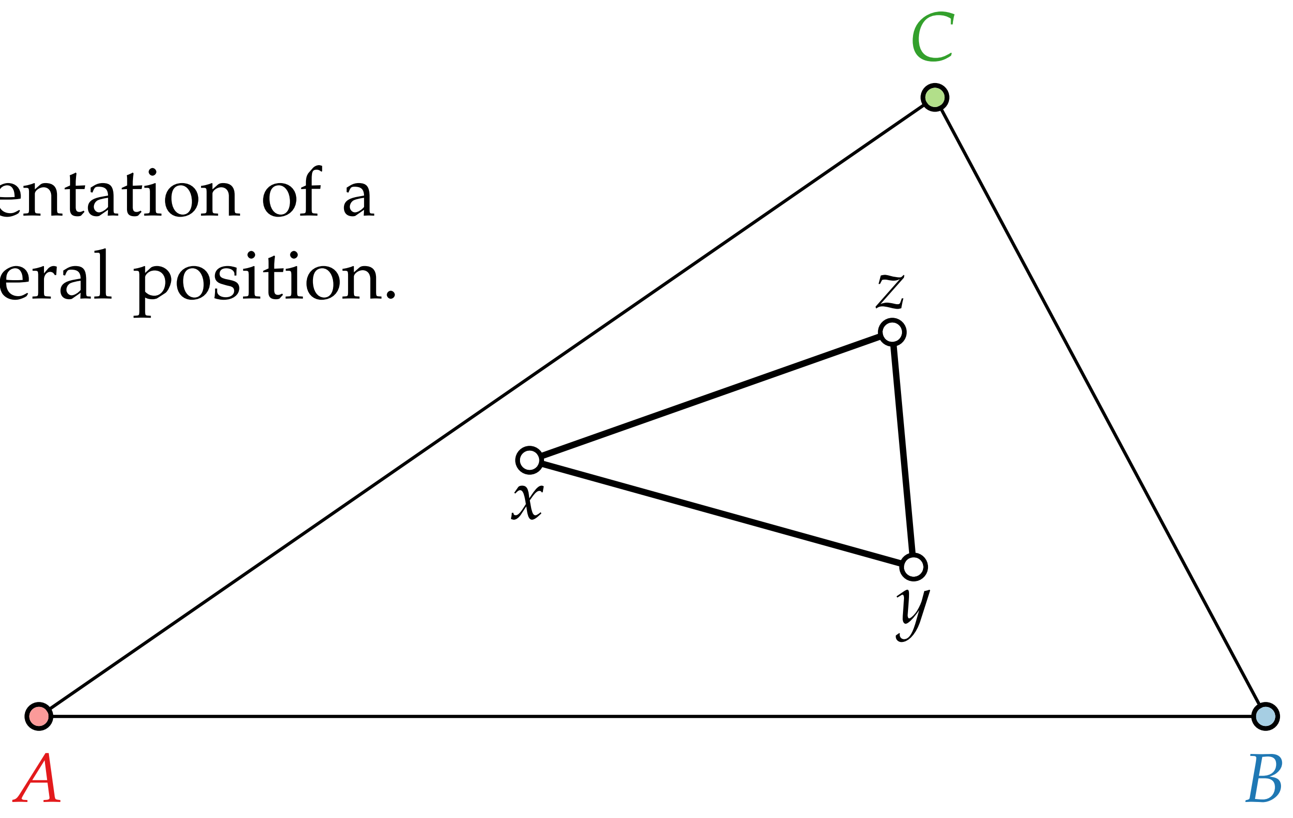

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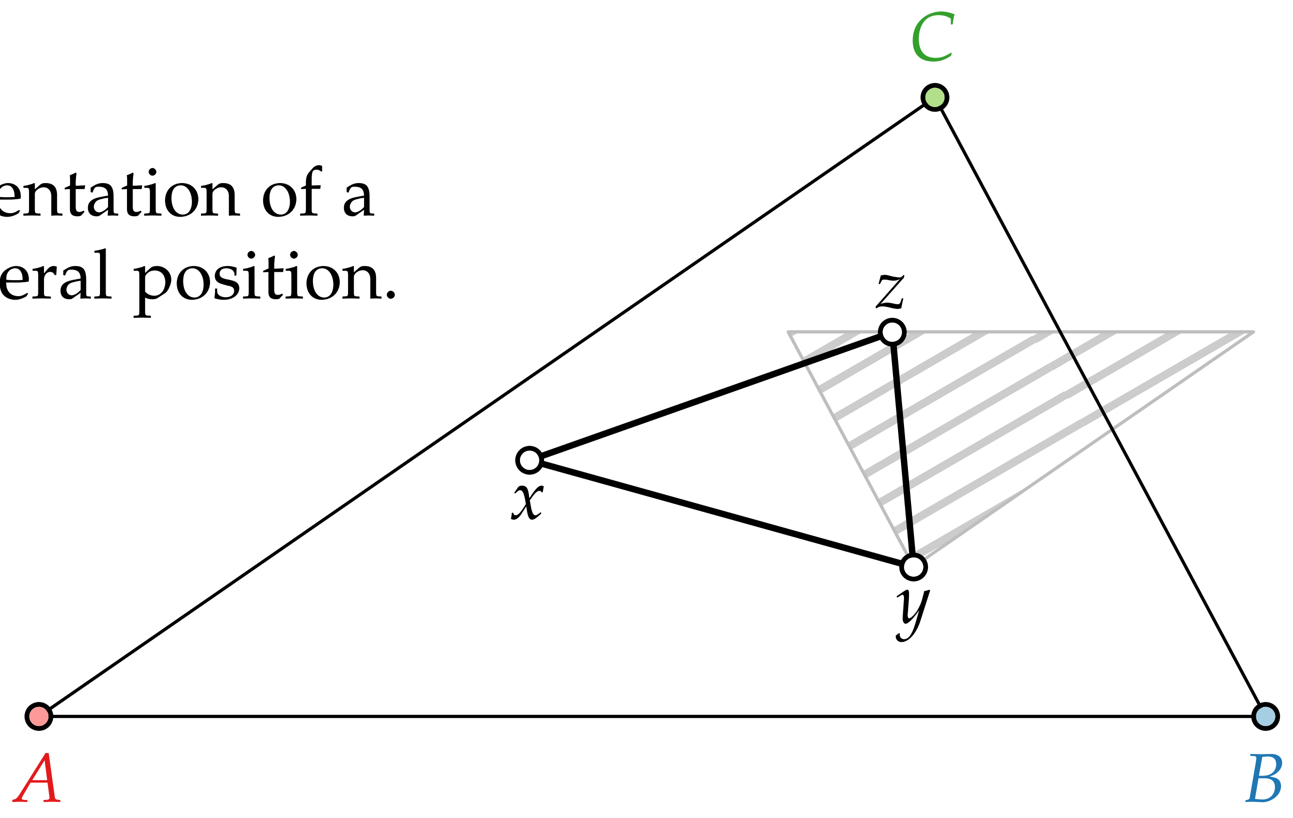

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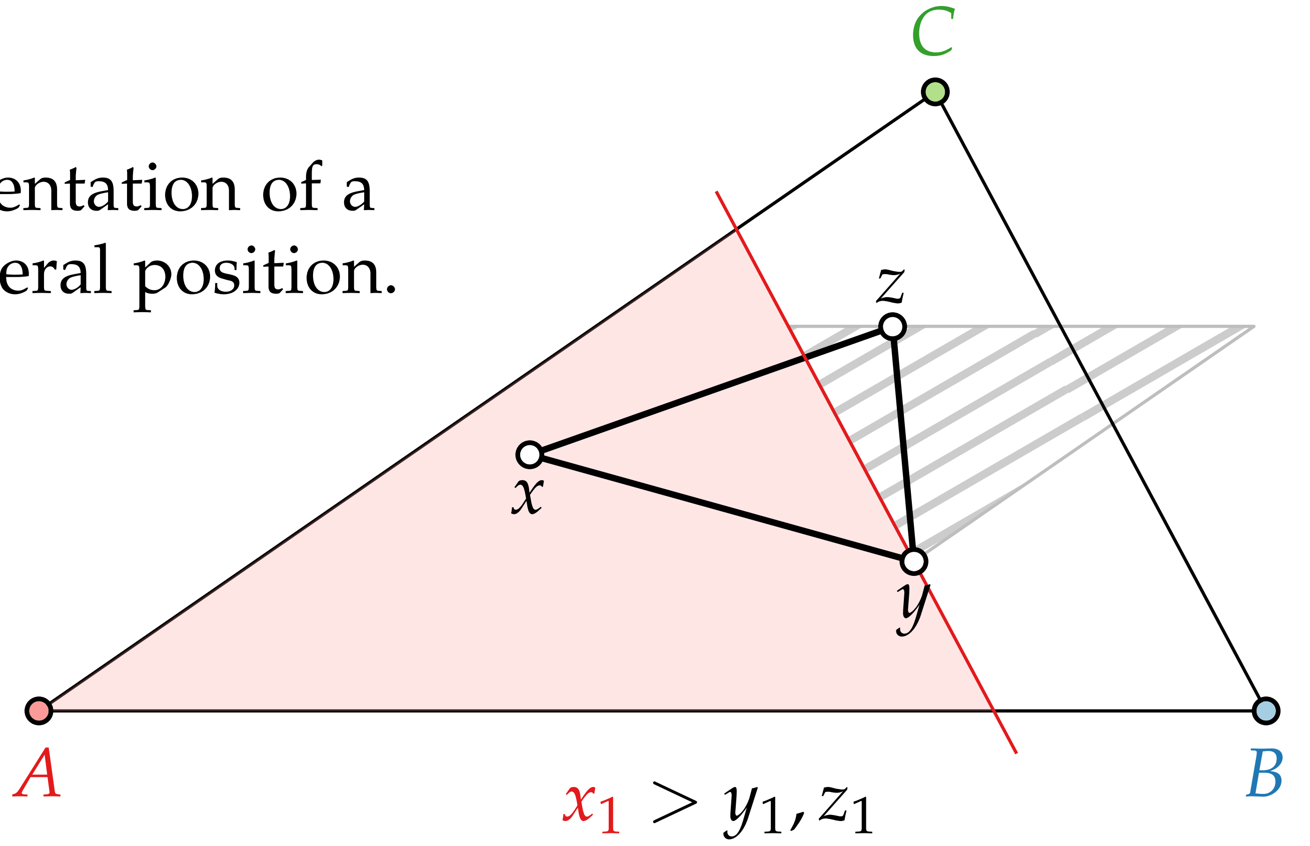

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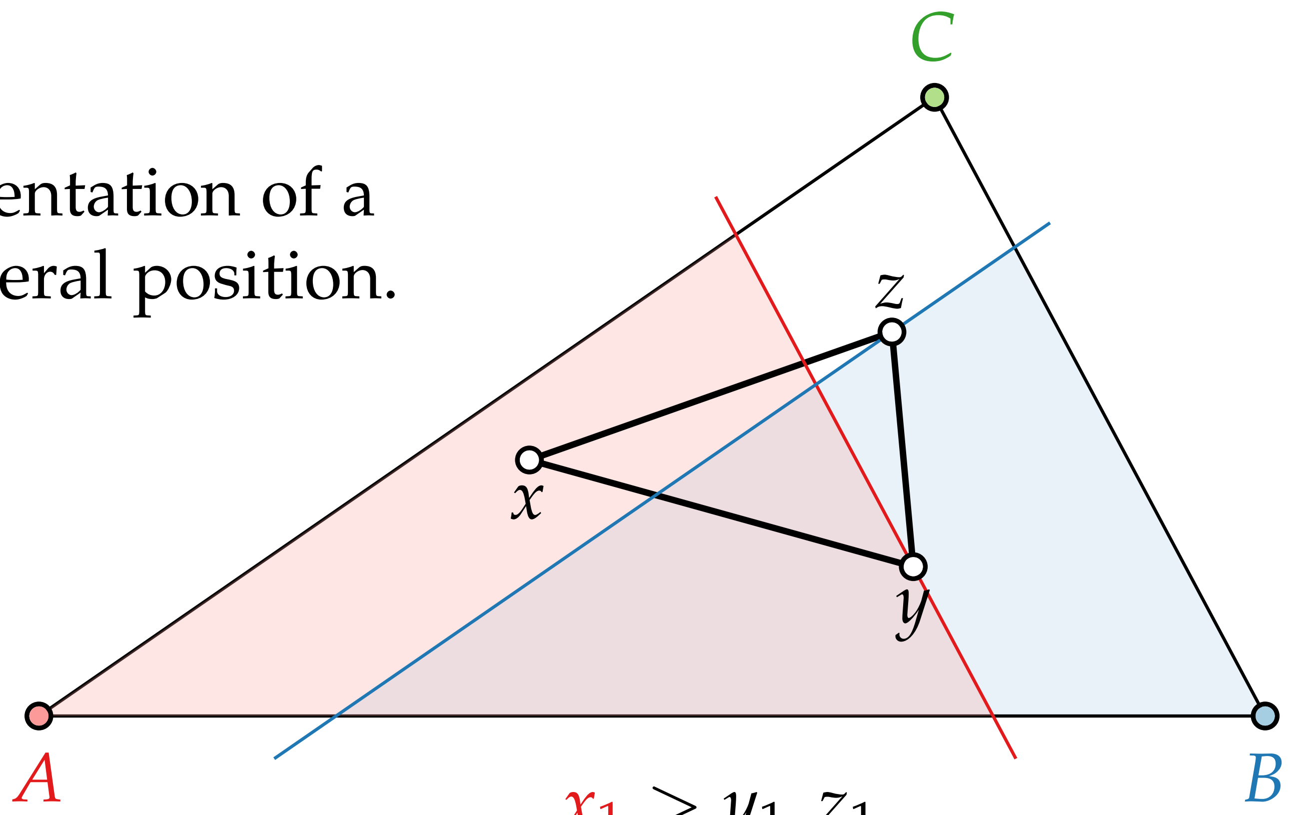

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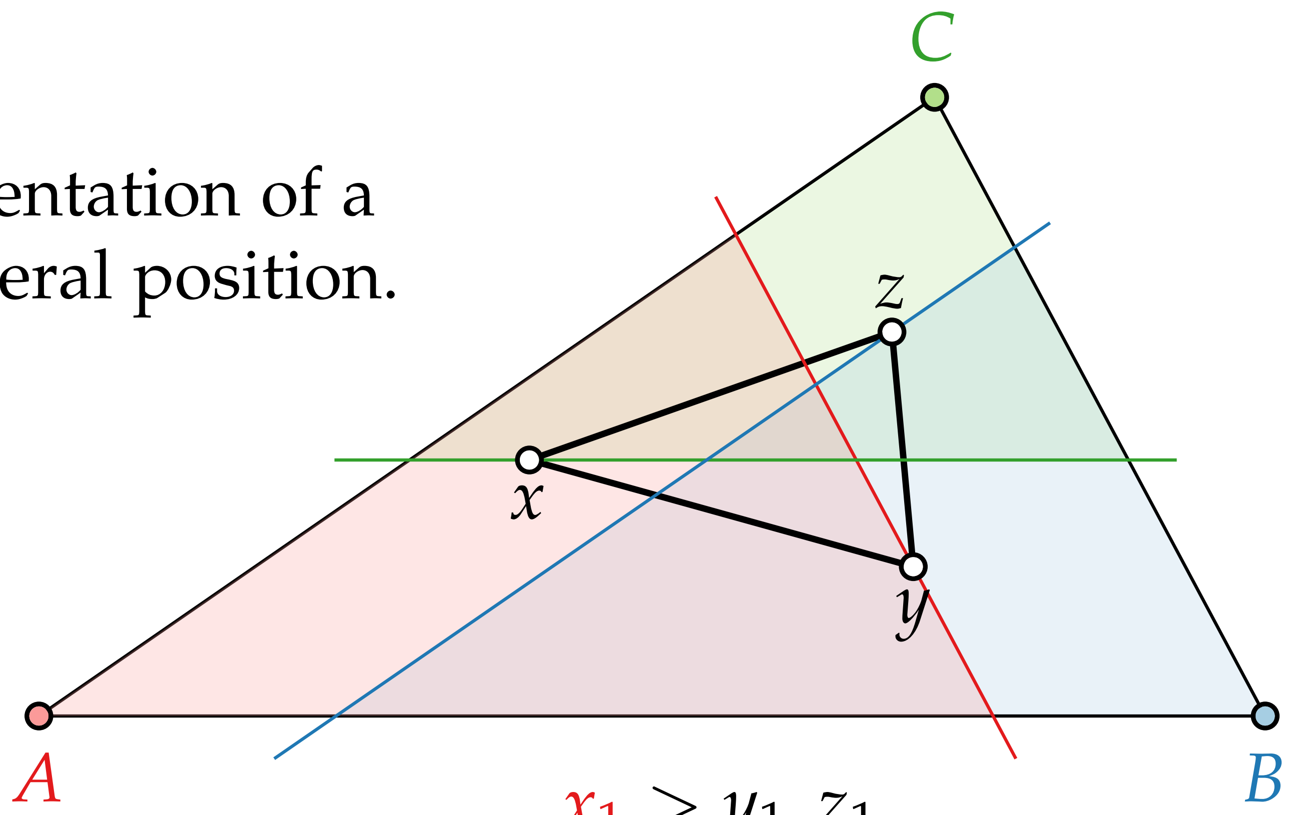

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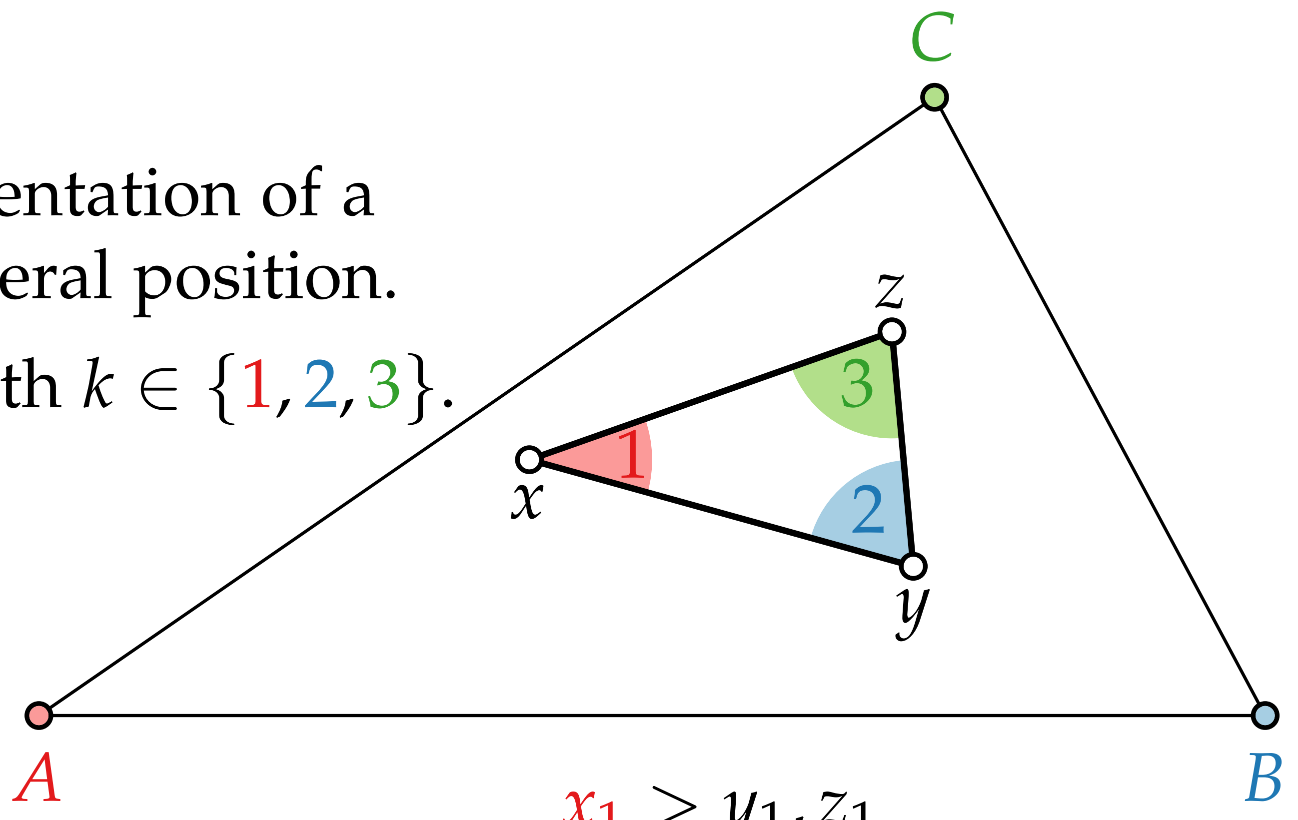
We can label each angle in $\triangle xyz$ **uniquely** with $k \in \{1, 2, 3\}$.



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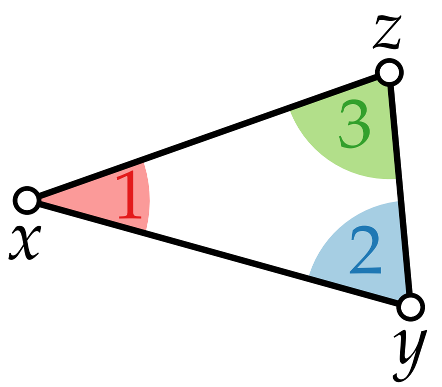

A **Schnyder Labeling** of a plane triangulation G is a labeling of all internal angles with labels 1, 2 and 3 such that:

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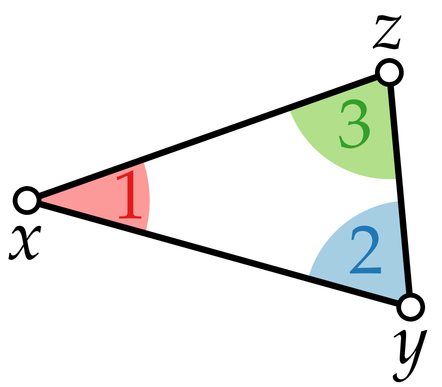

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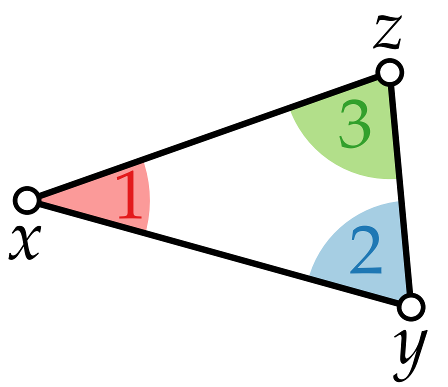

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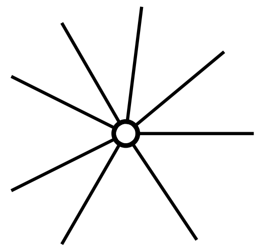

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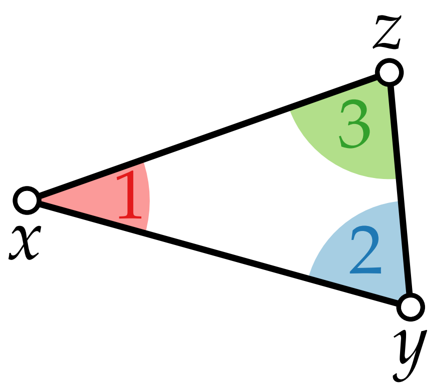

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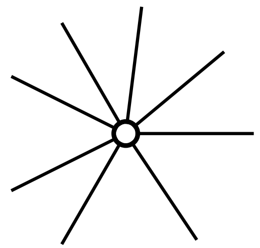

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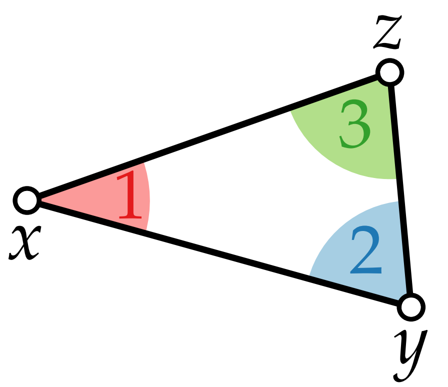

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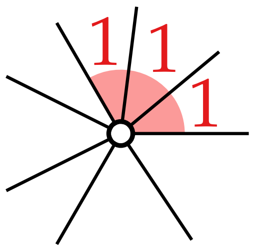
- a nonempty interval of 1's



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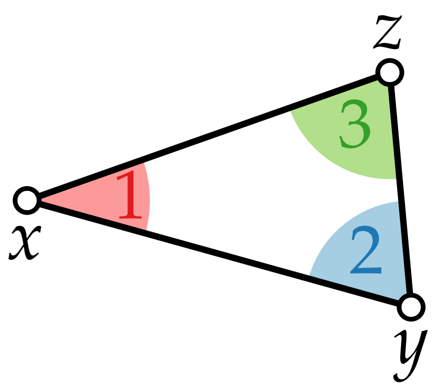

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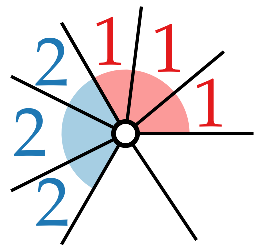

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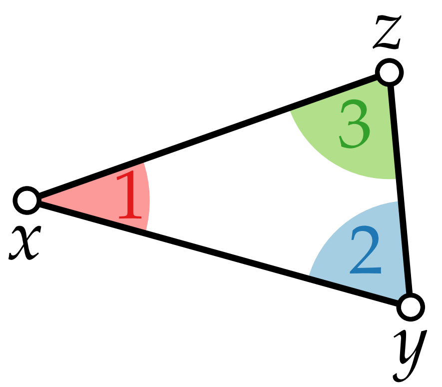

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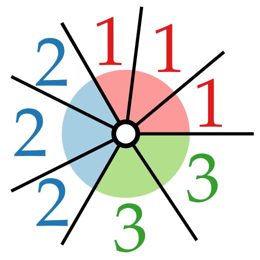

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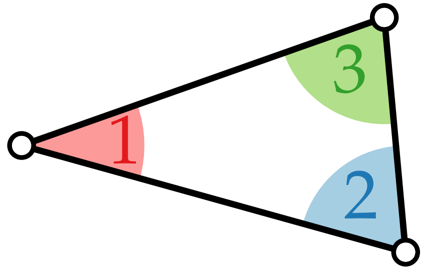

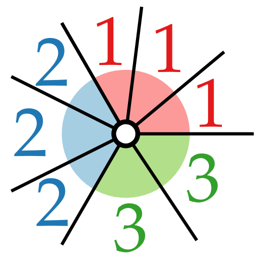

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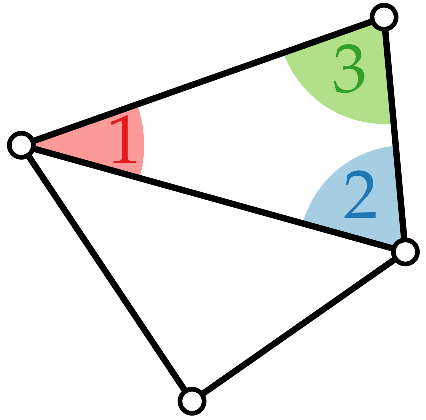

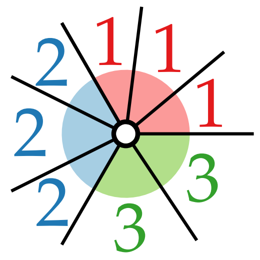

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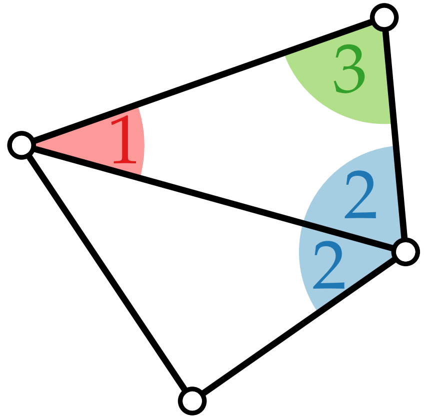

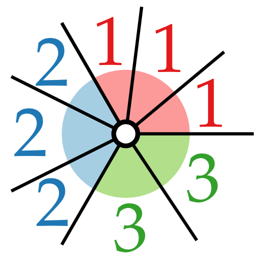

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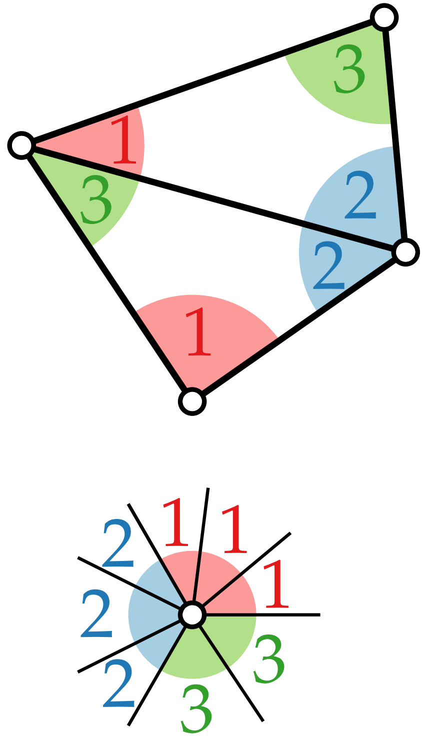

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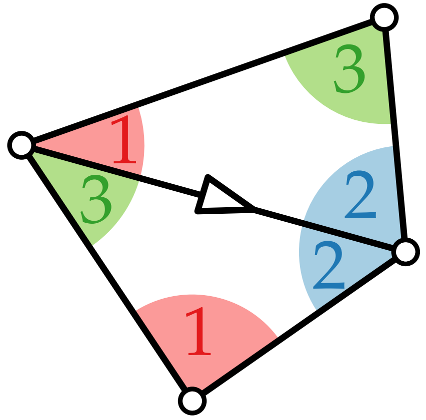

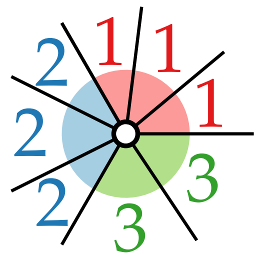

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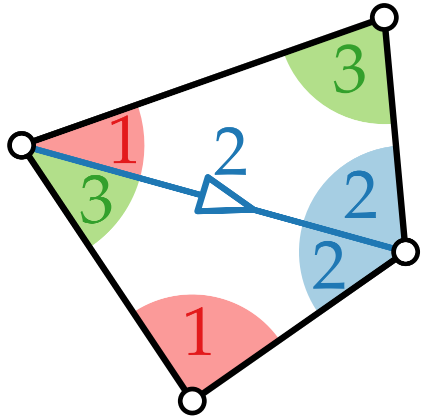

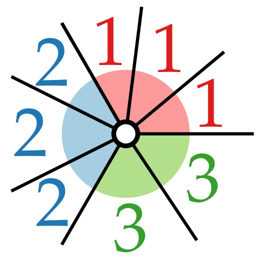

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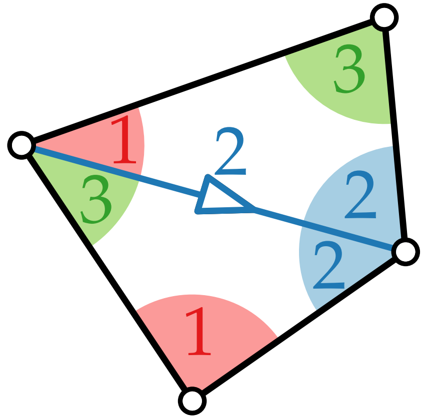

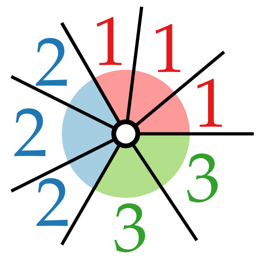

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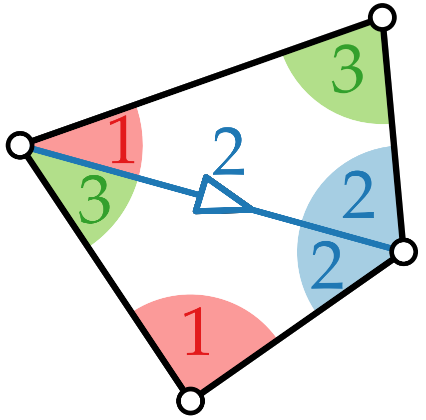

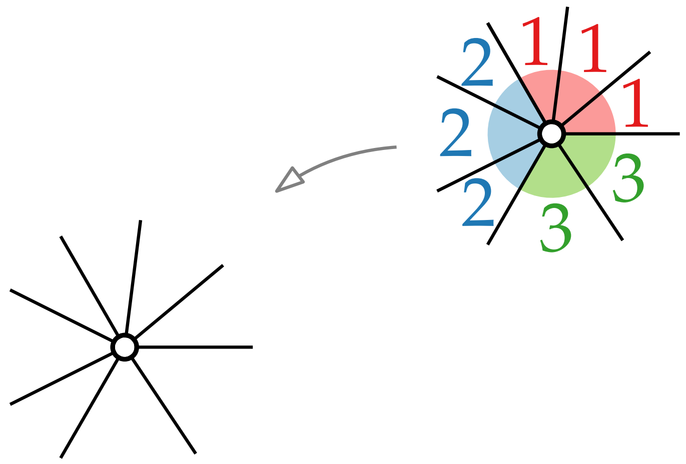

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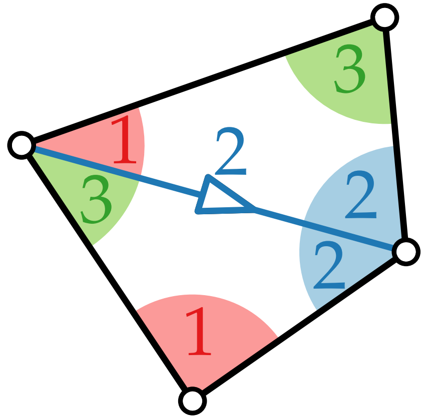

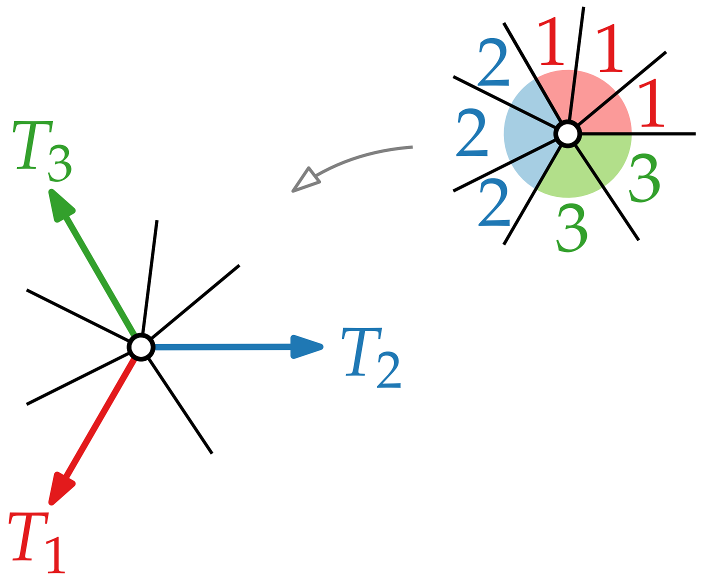

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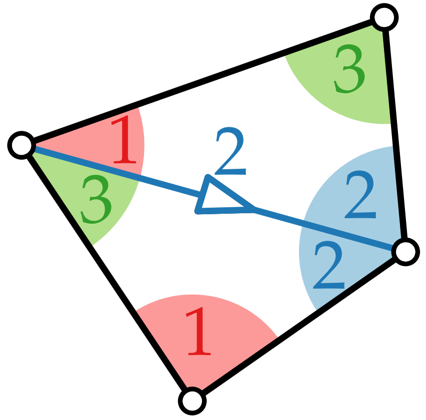

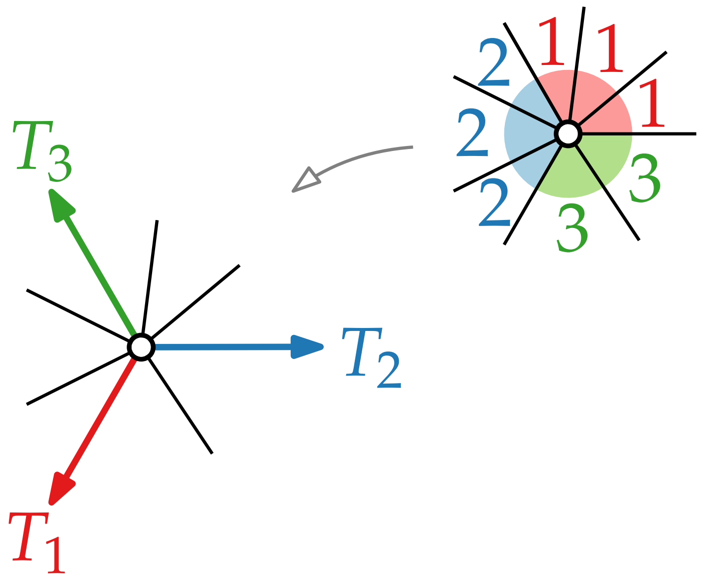

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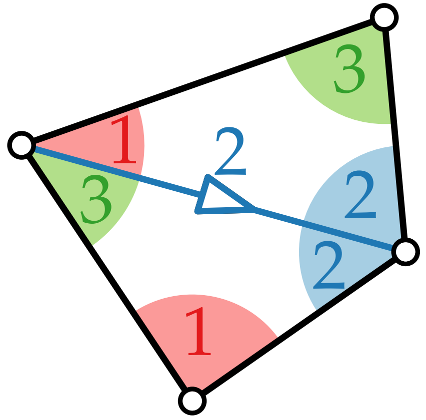
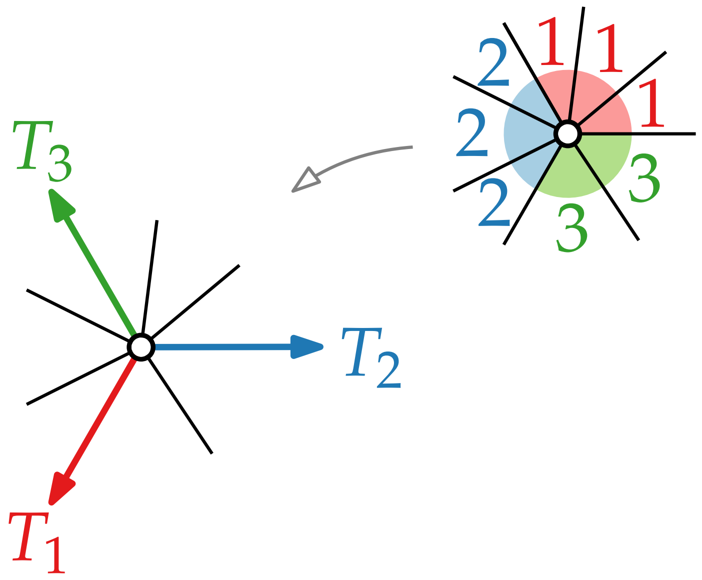
  leaving in T_1





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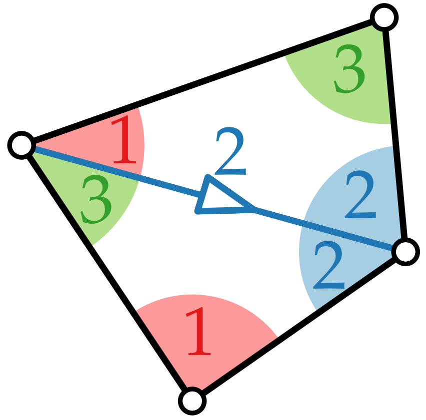

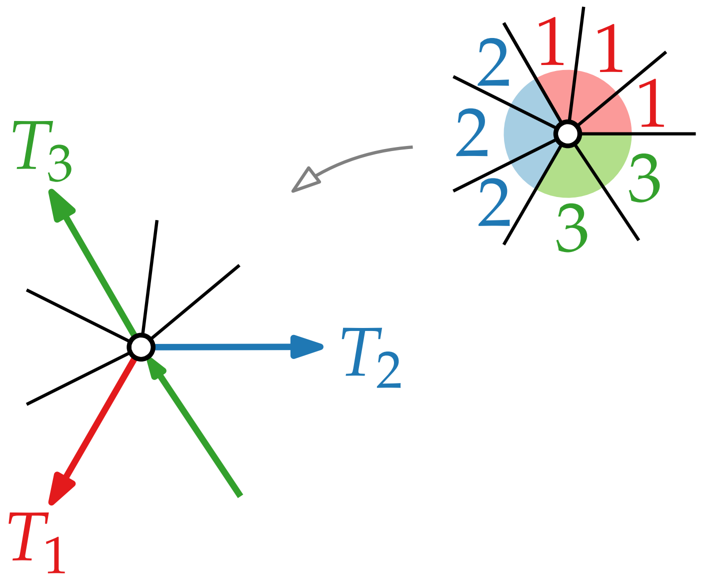

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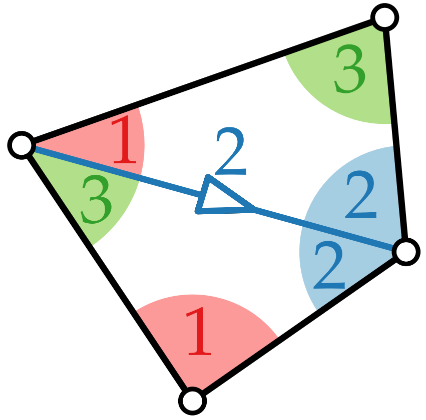

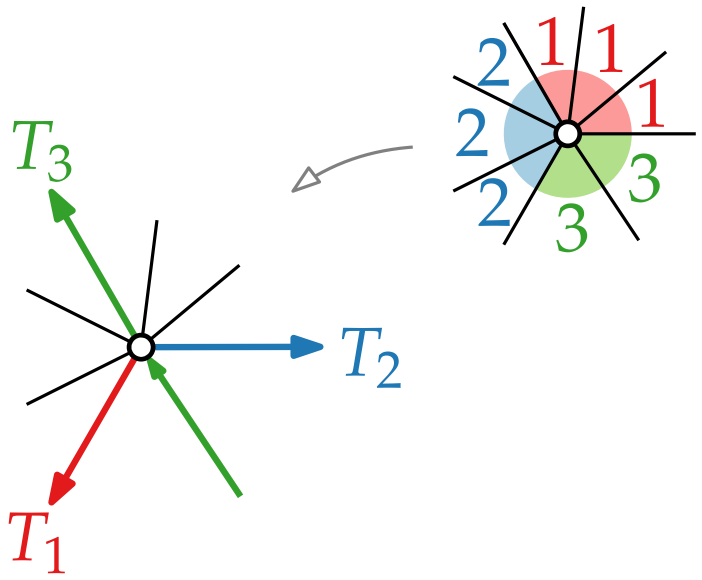

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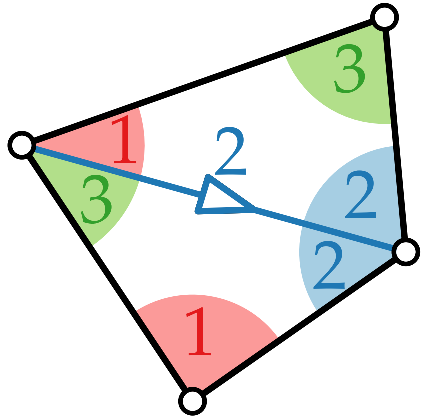

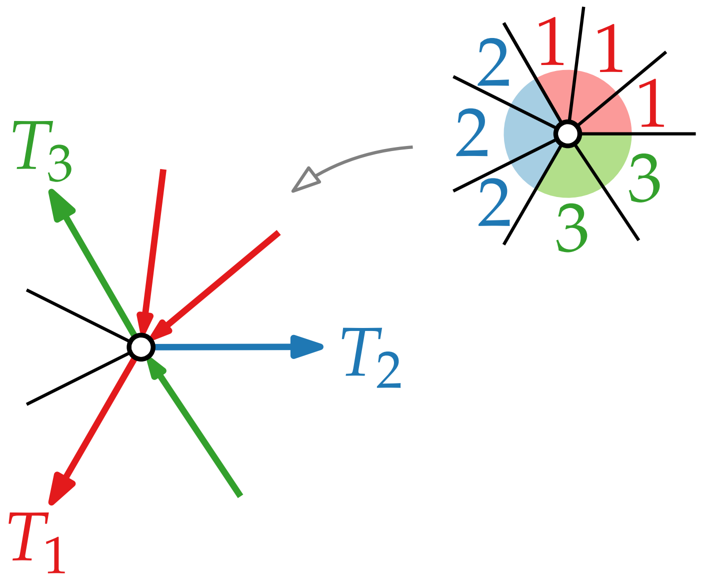

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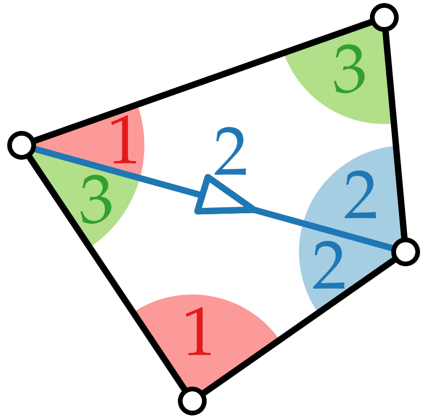

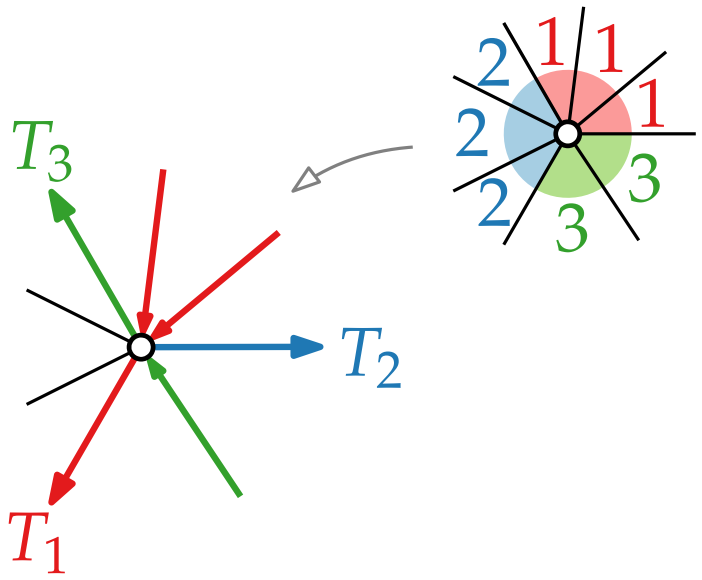

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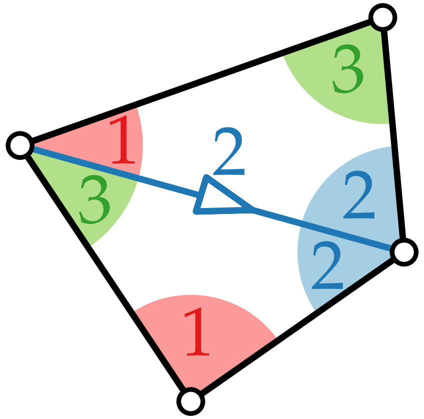
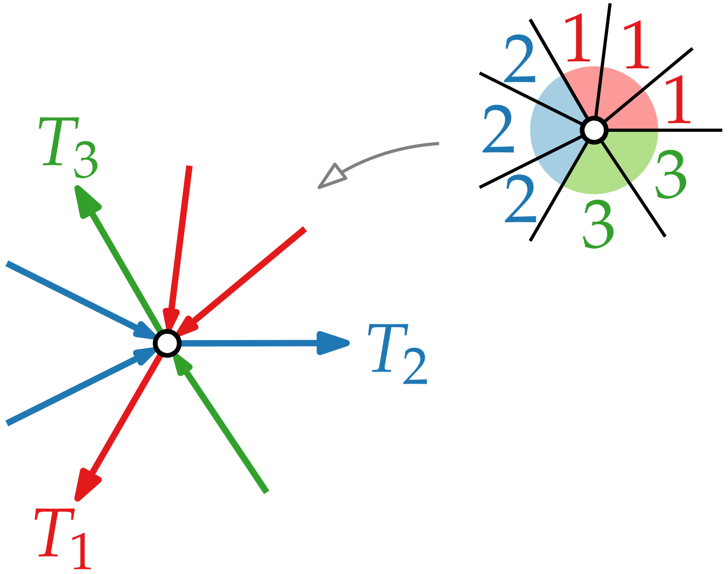
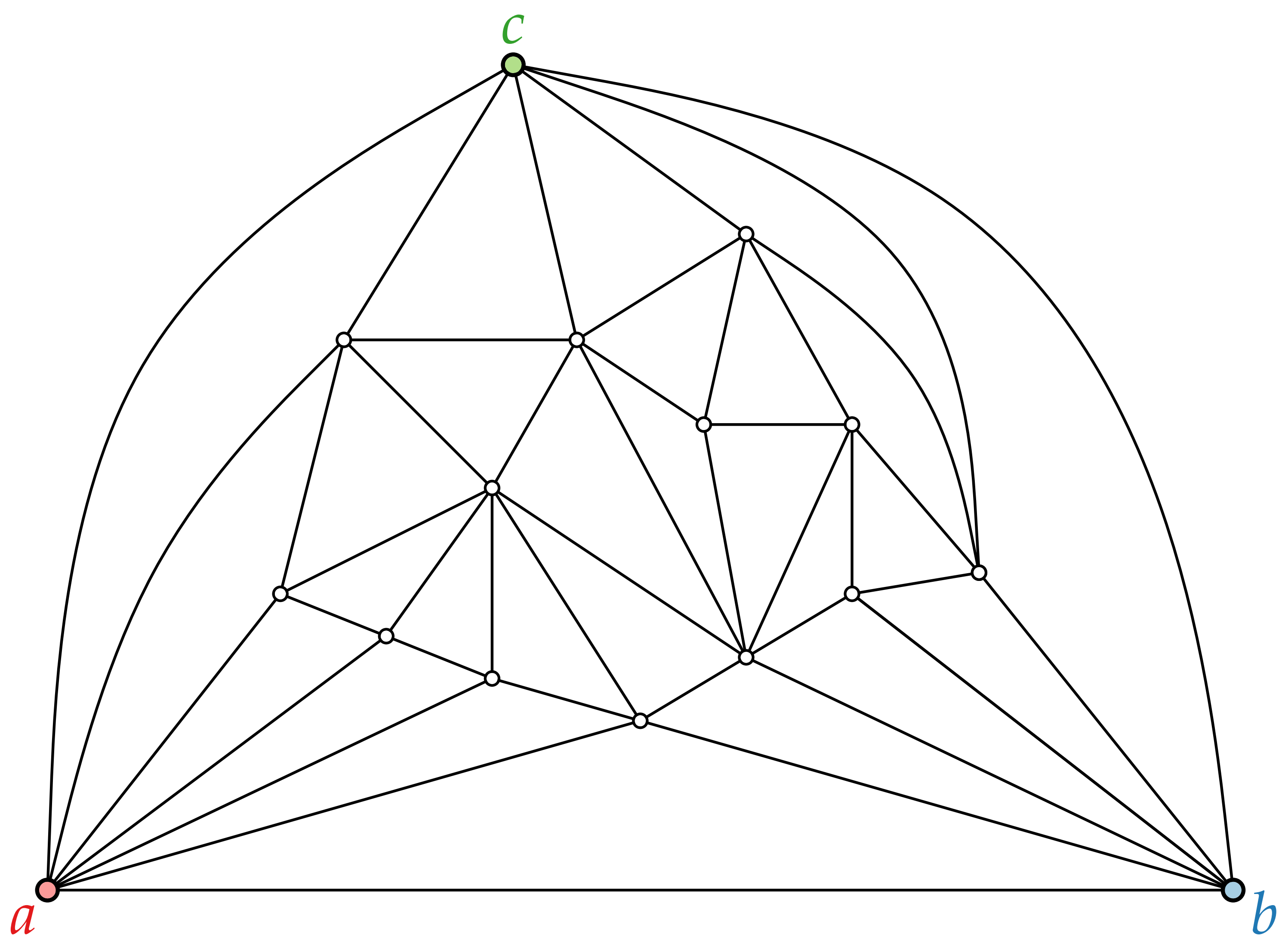
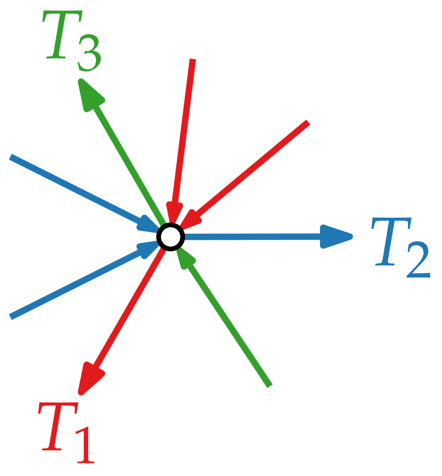




Schnyder Realizer – Example and Properties





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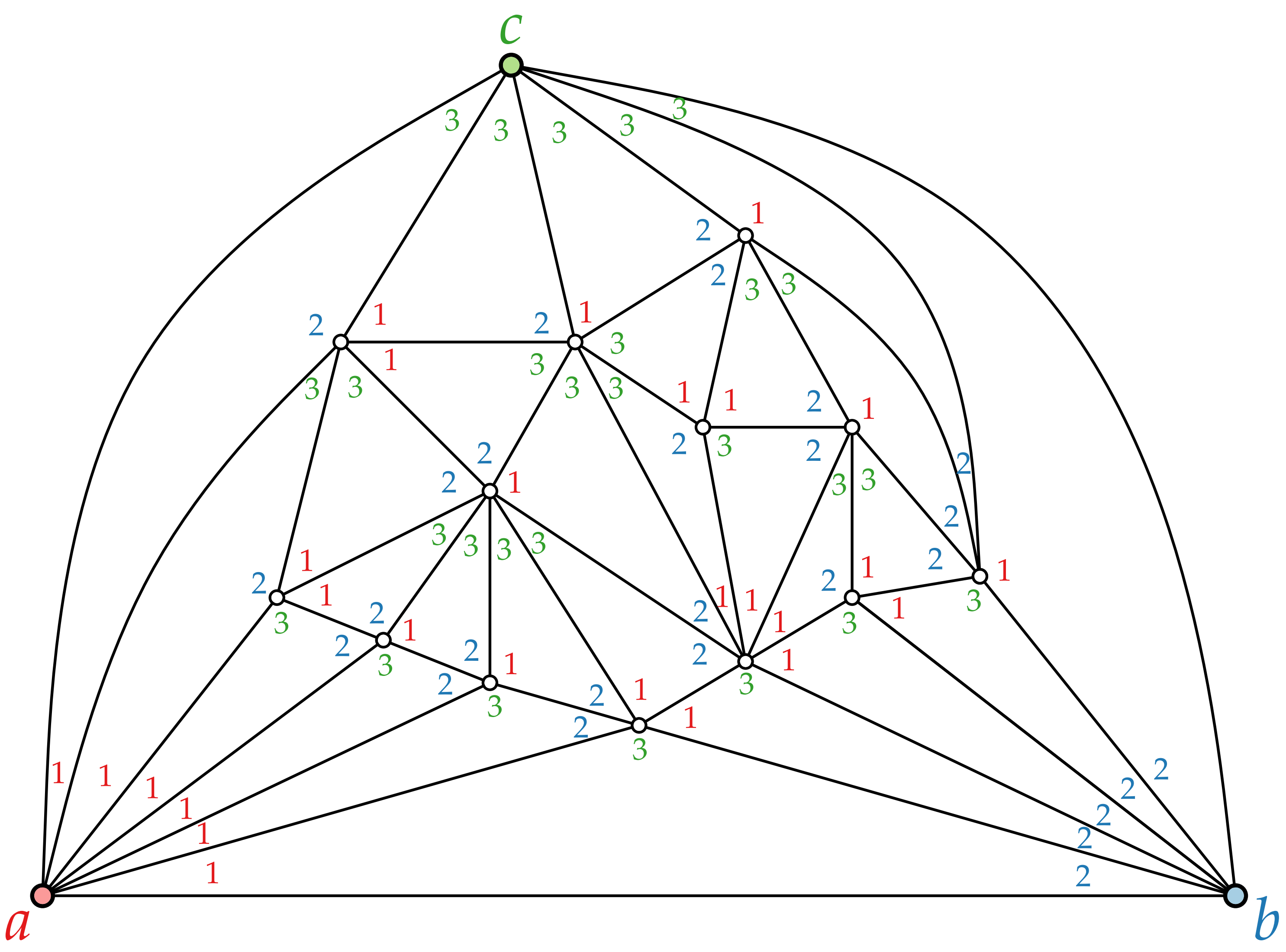

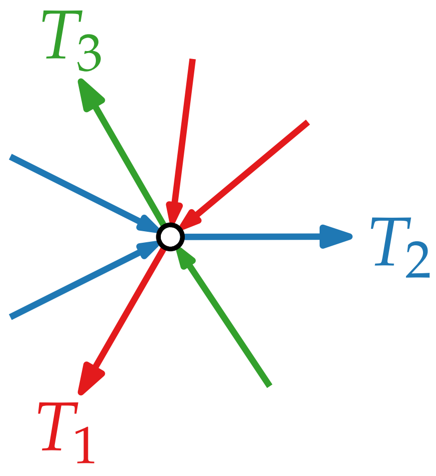

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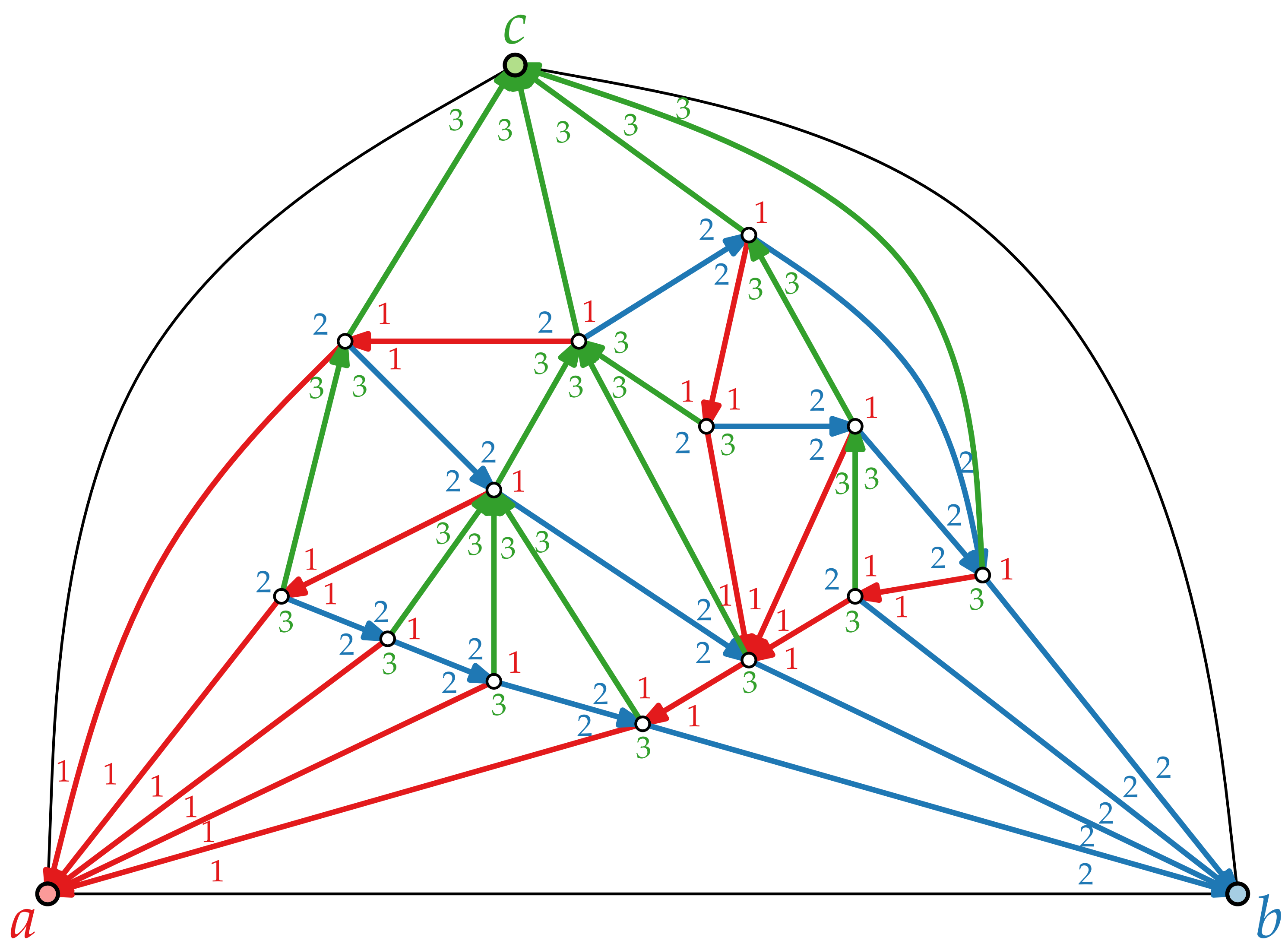

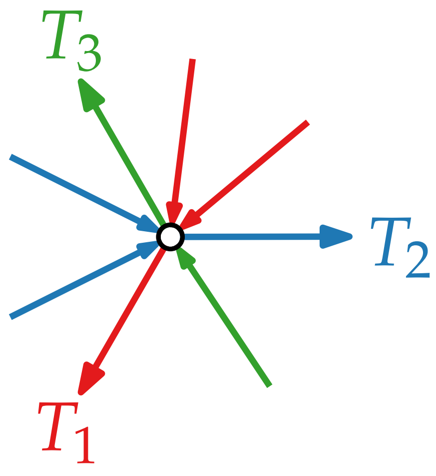

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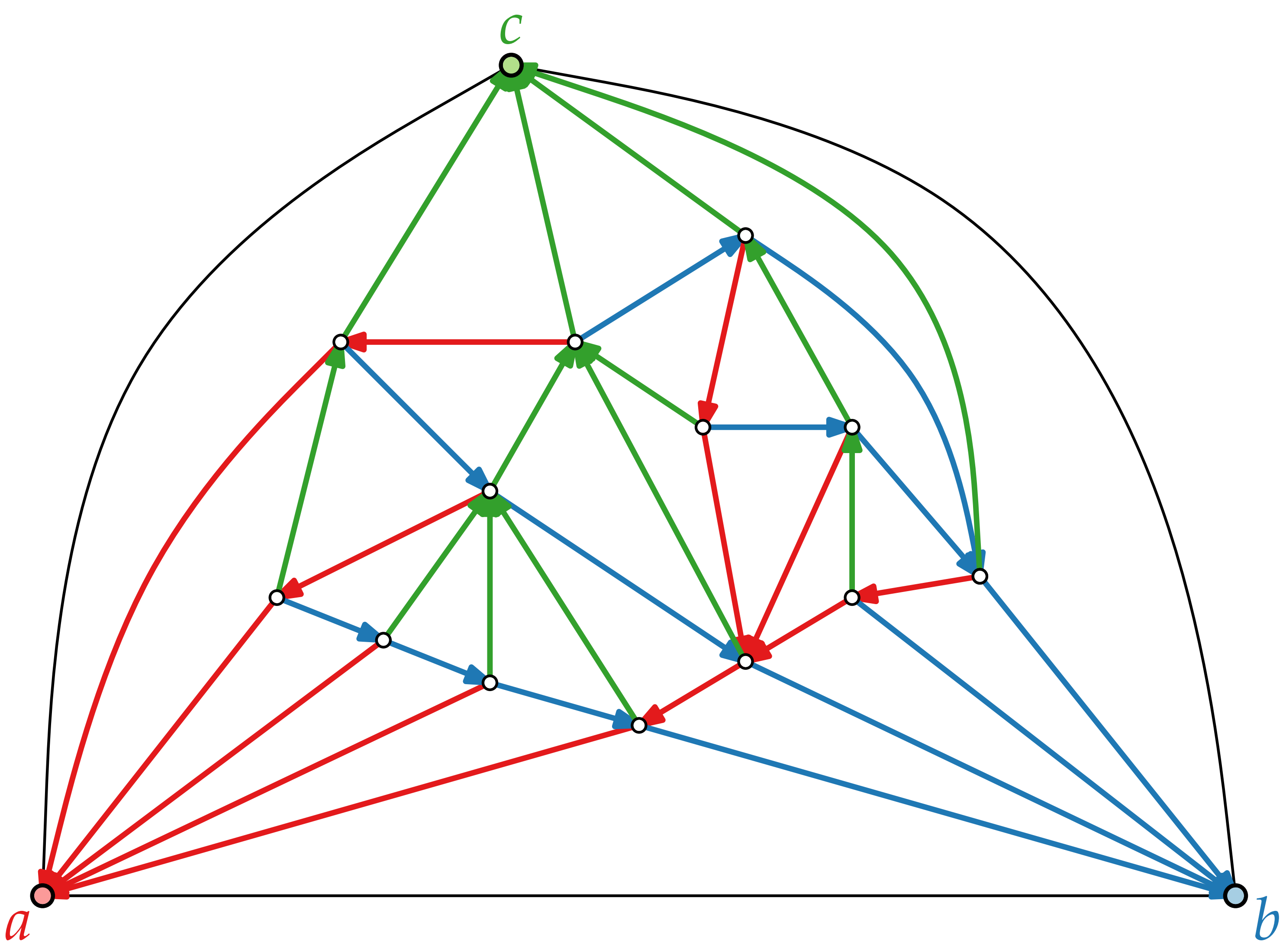

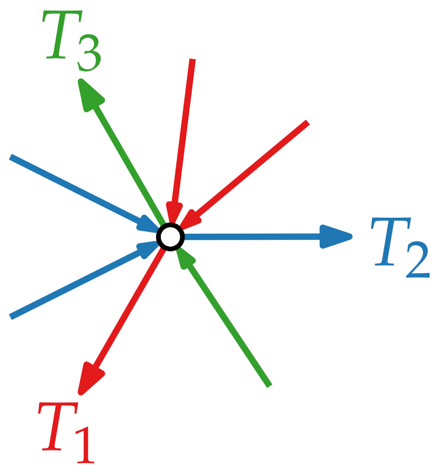

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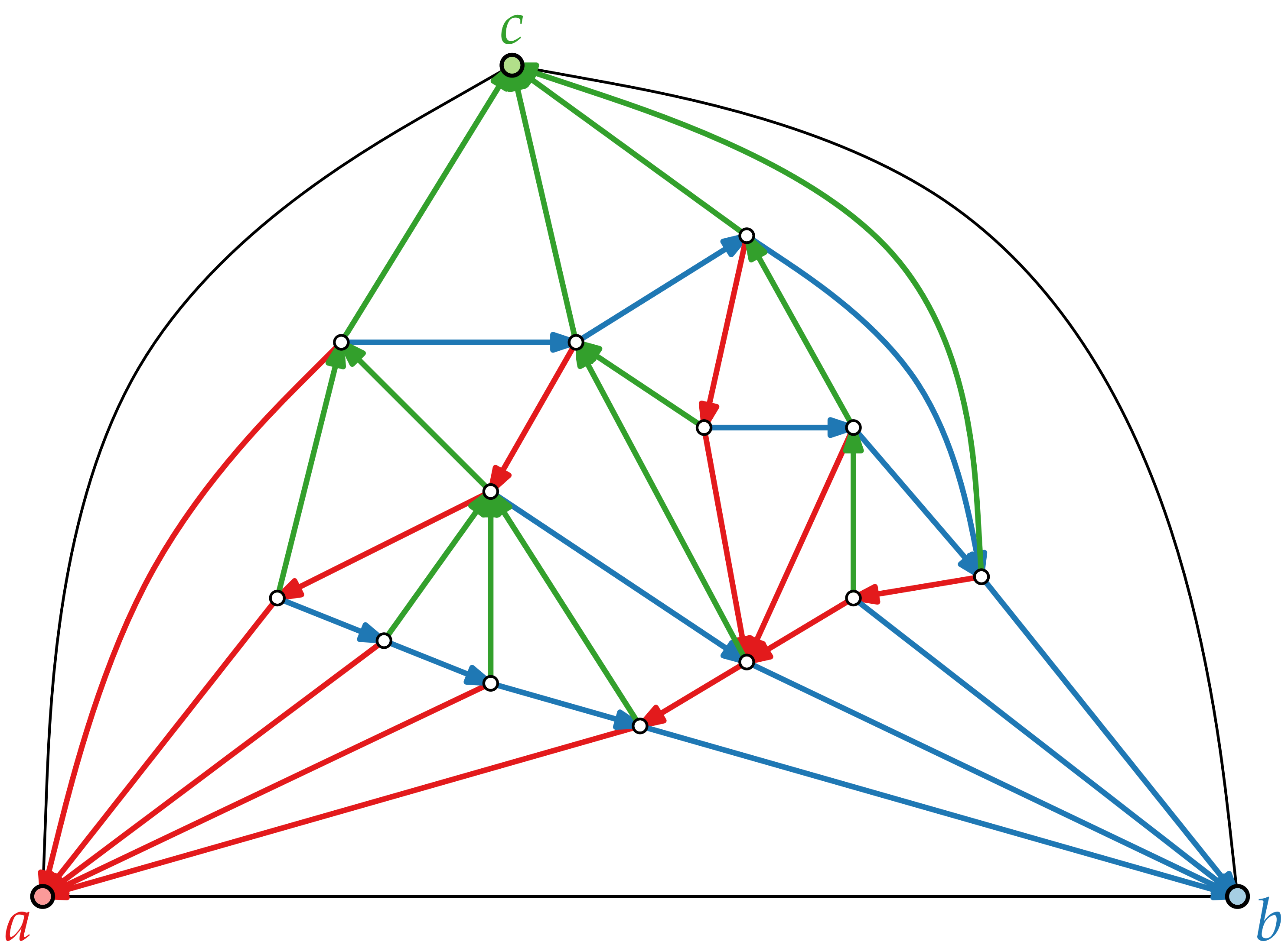

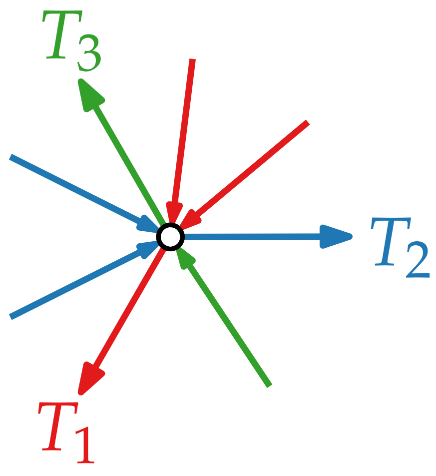

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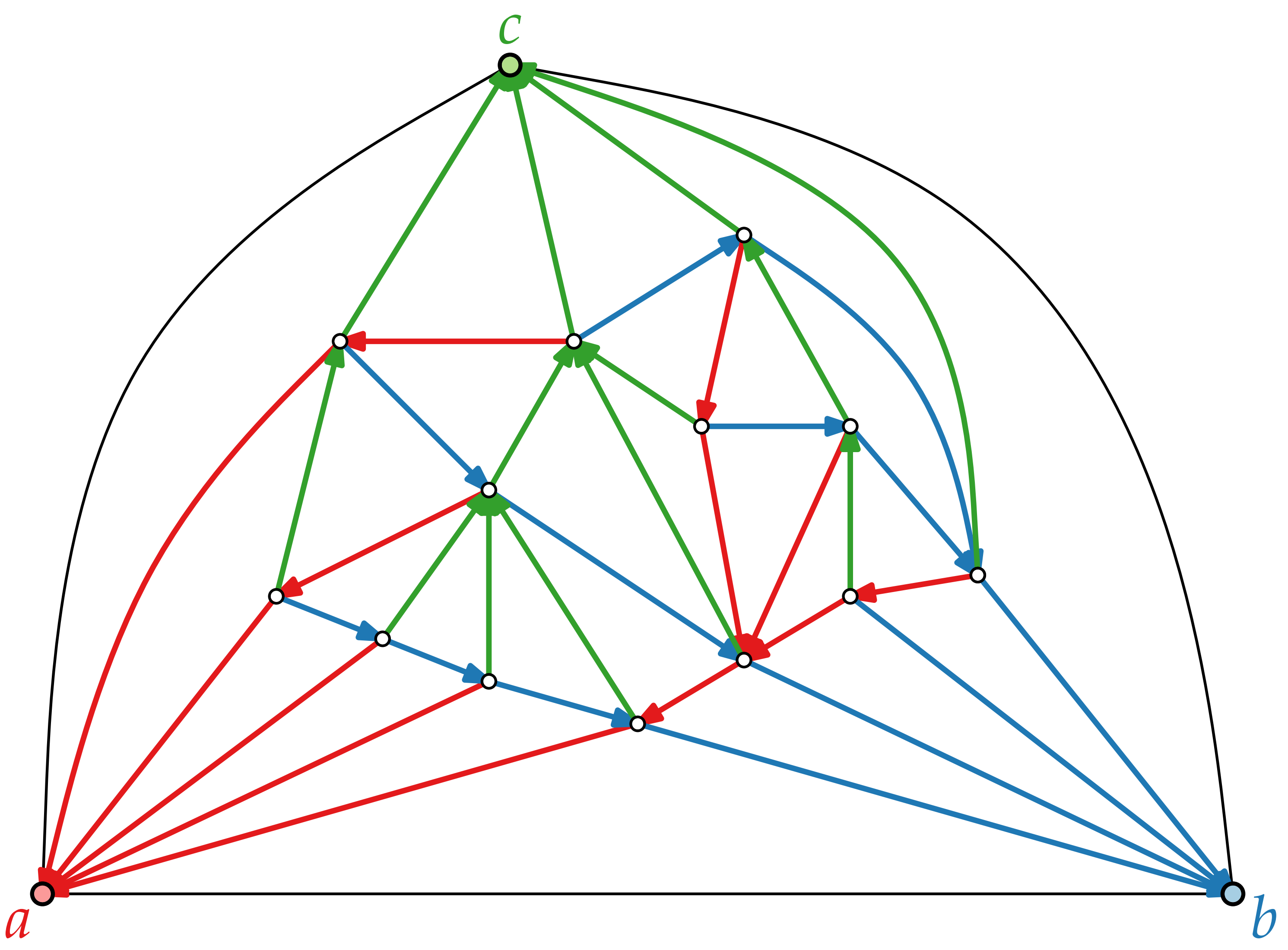
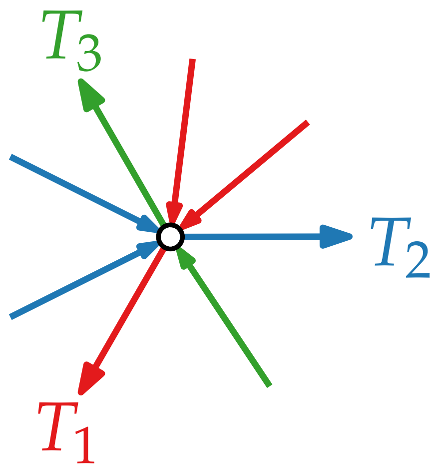
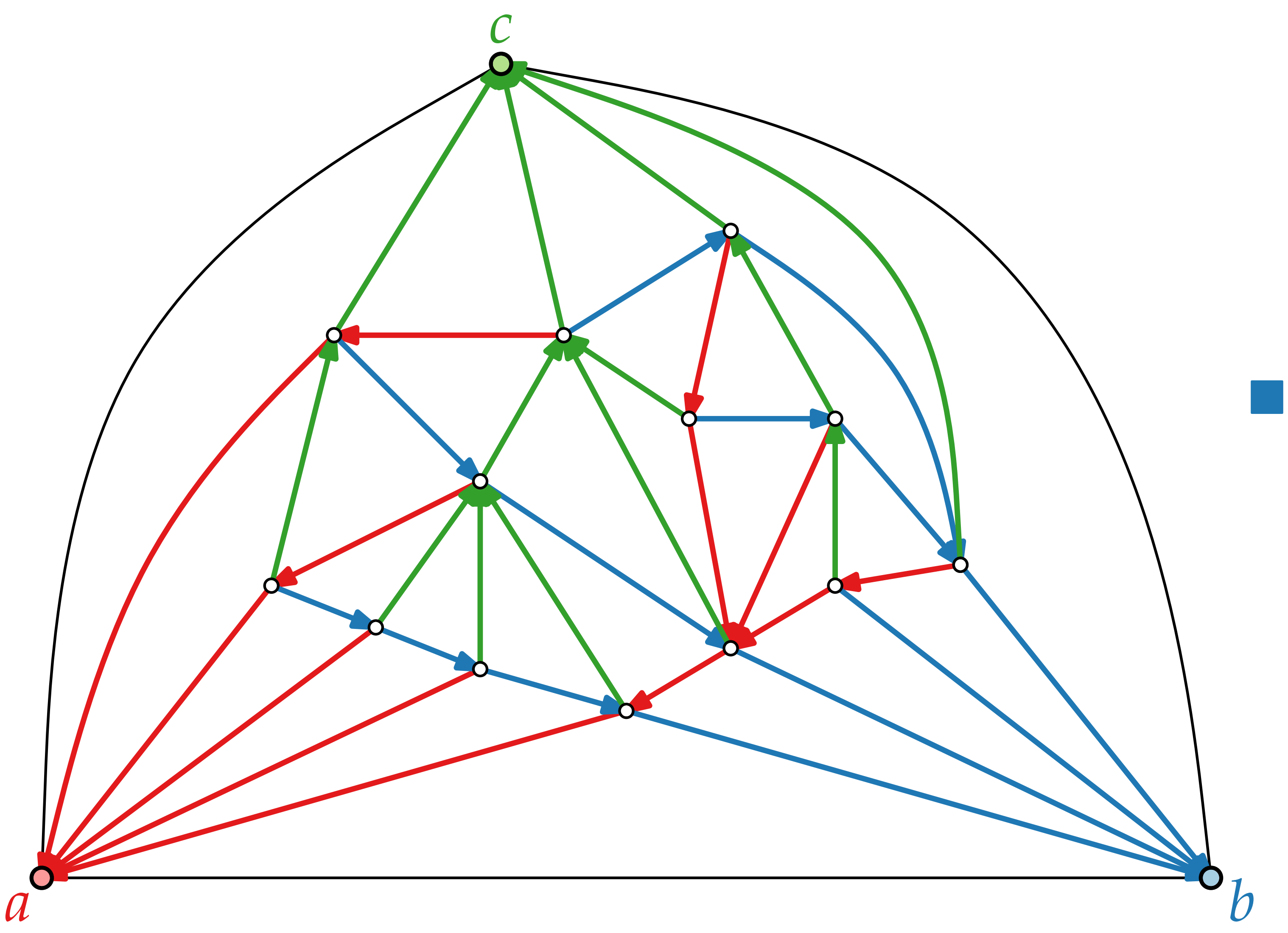
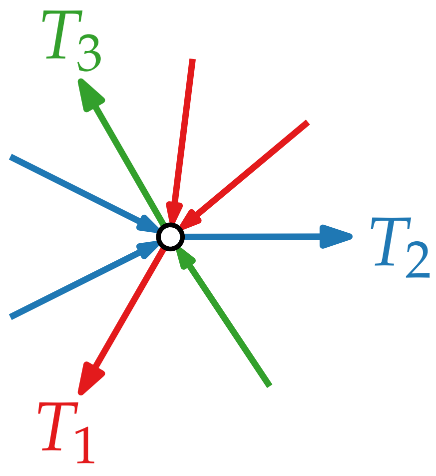




Schnyder Realizer – Example and Properties





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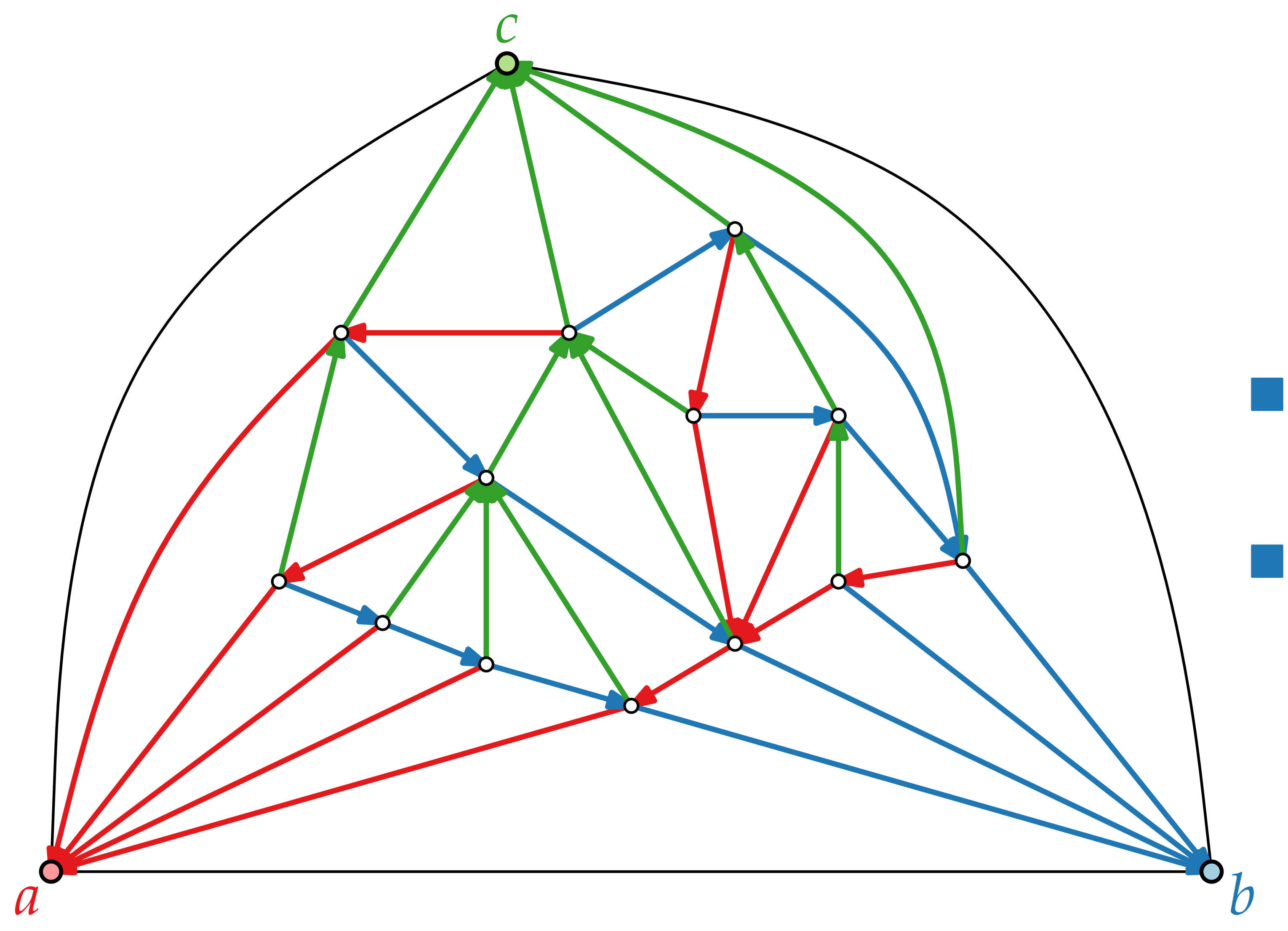

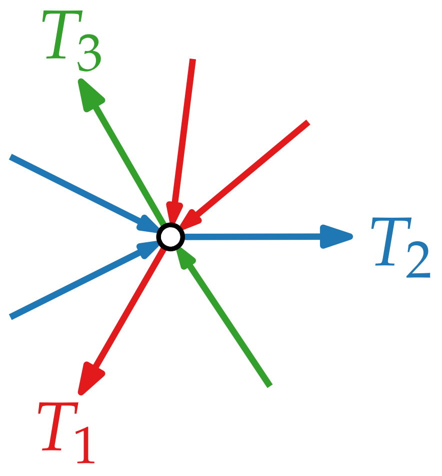

- All inner edges incident to *a*, *b*, and *c* are incoming in the same color.
- T_1, T_2, and T_3 are trees on all inner vertices and one outer vertex each (as its root).

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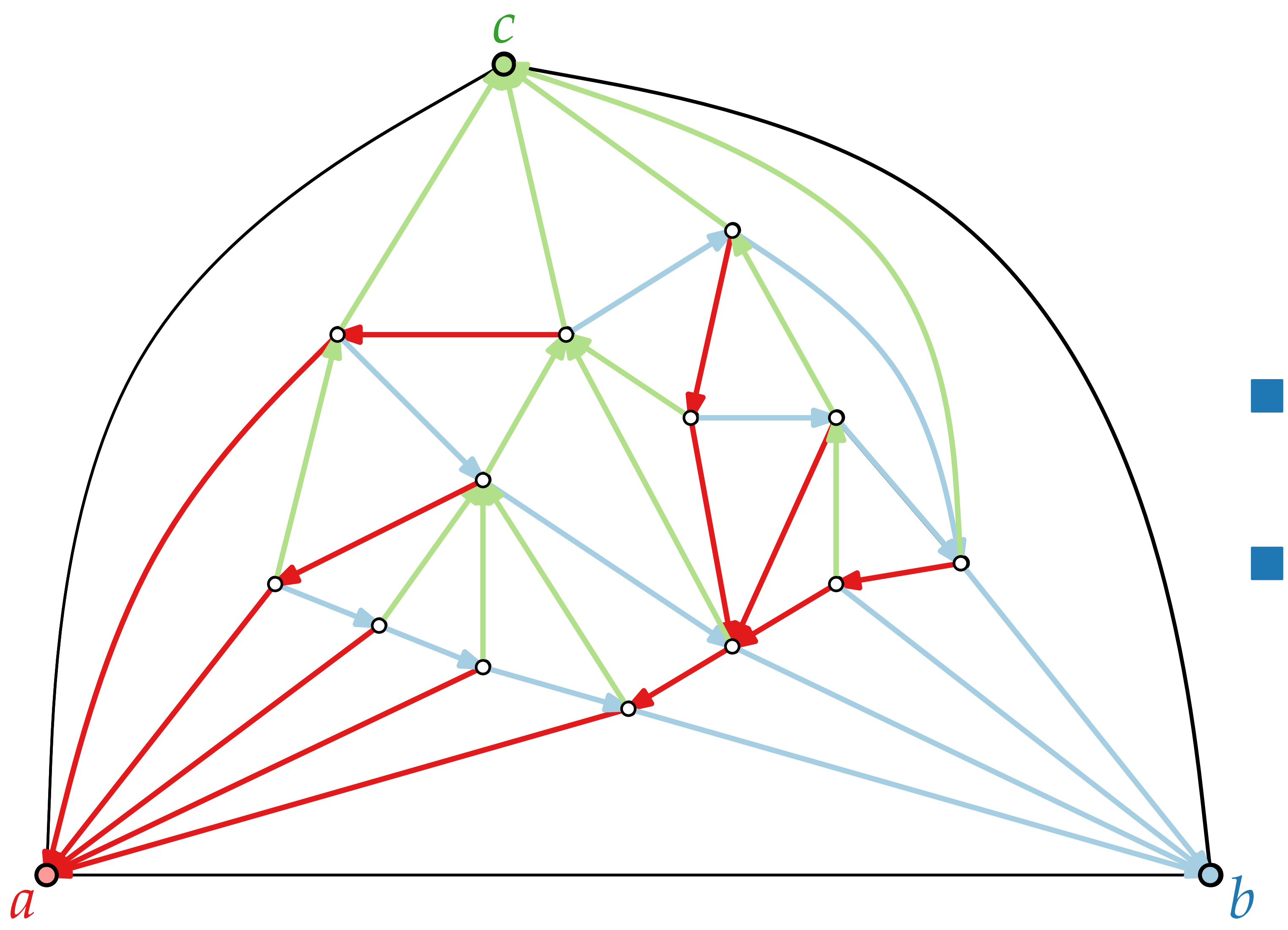

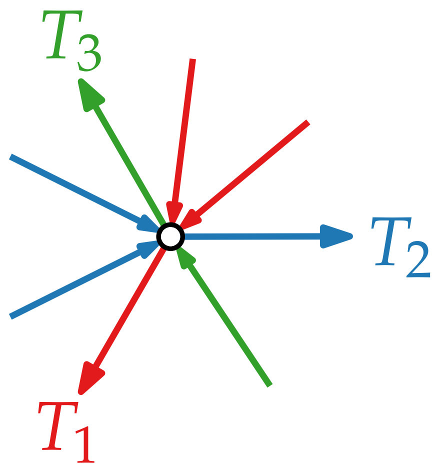

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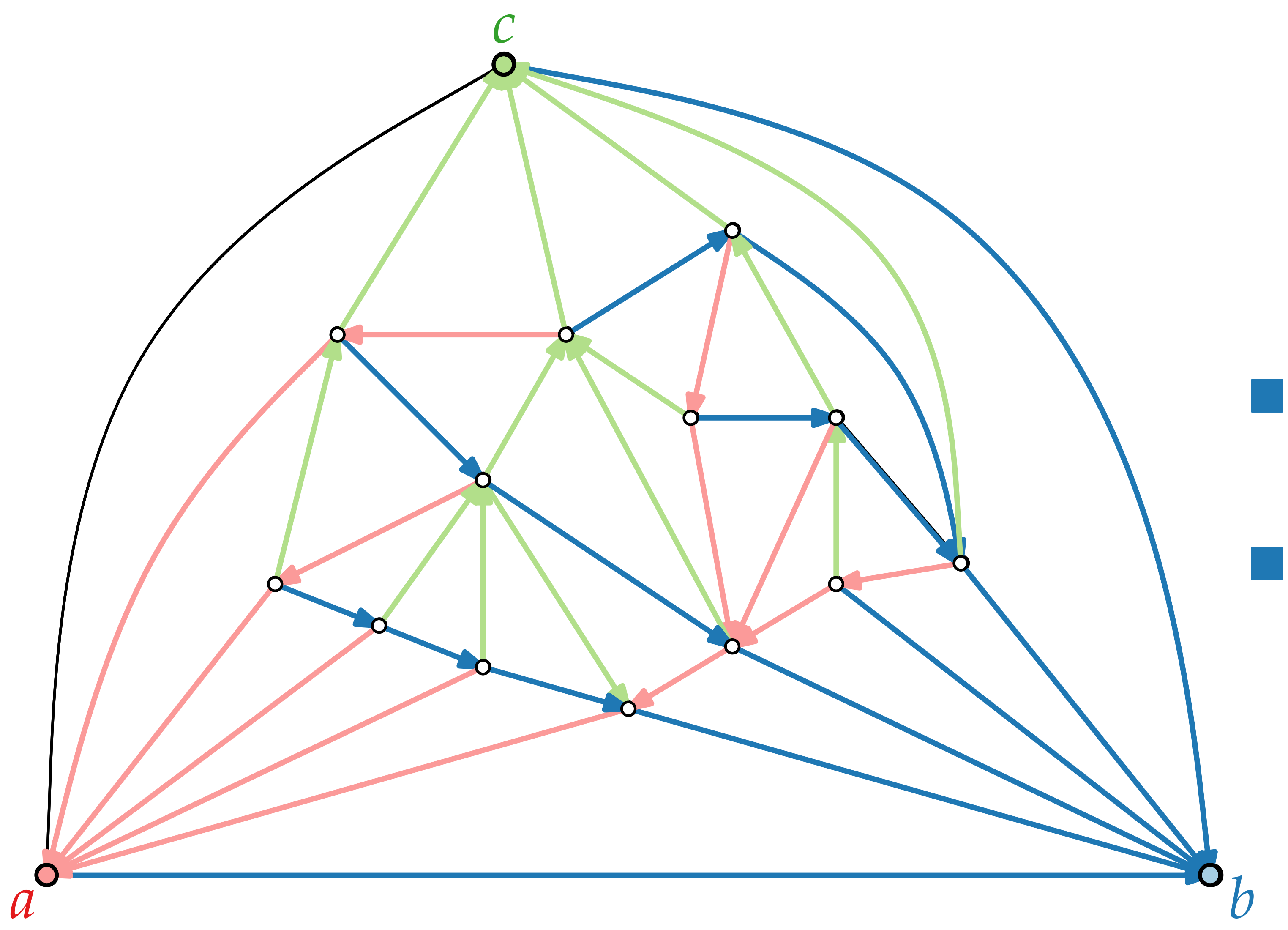

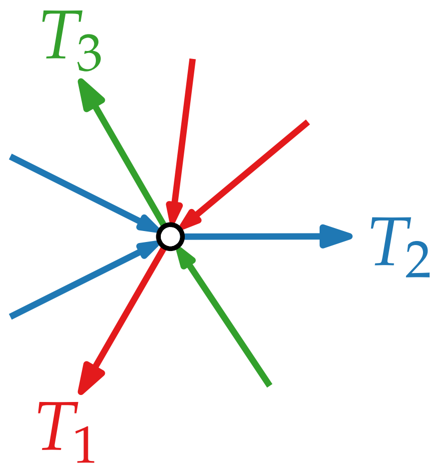

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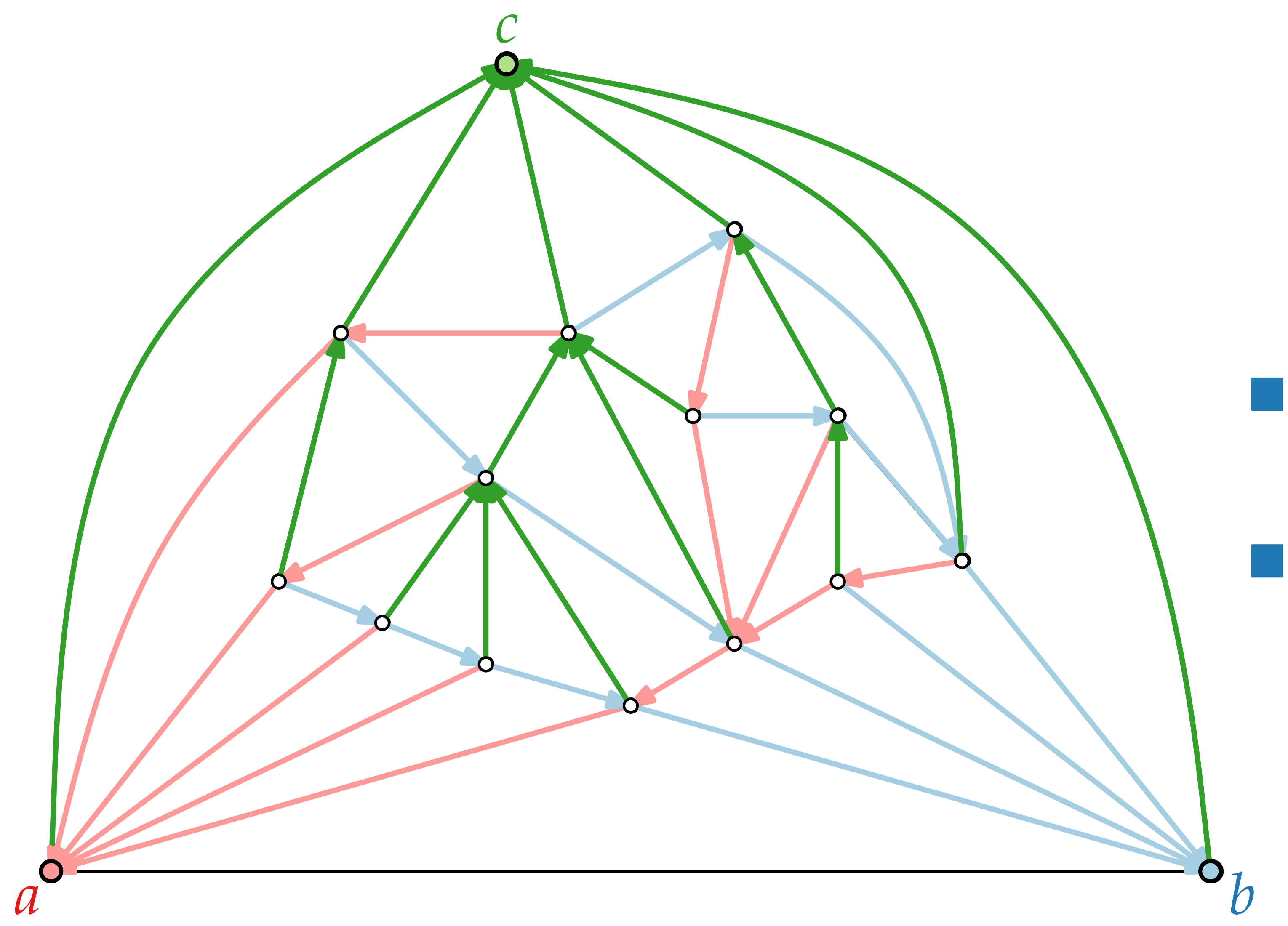

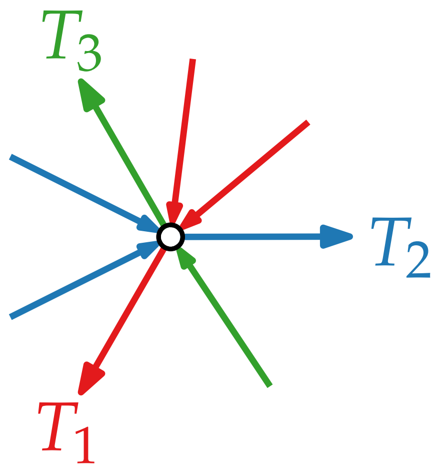

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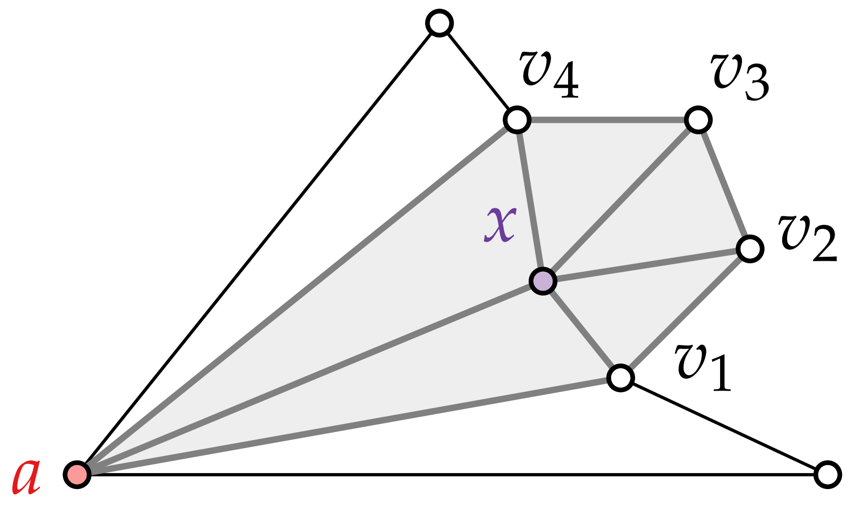
Schnyder Realizer – Existence



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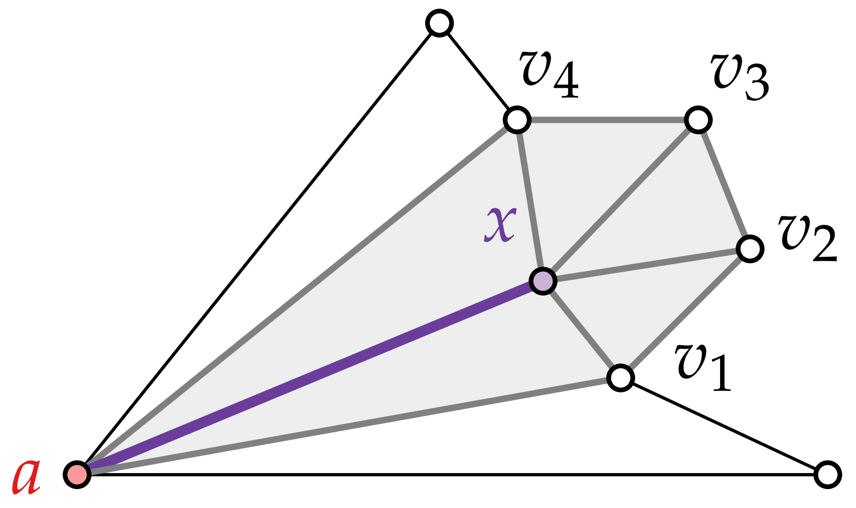

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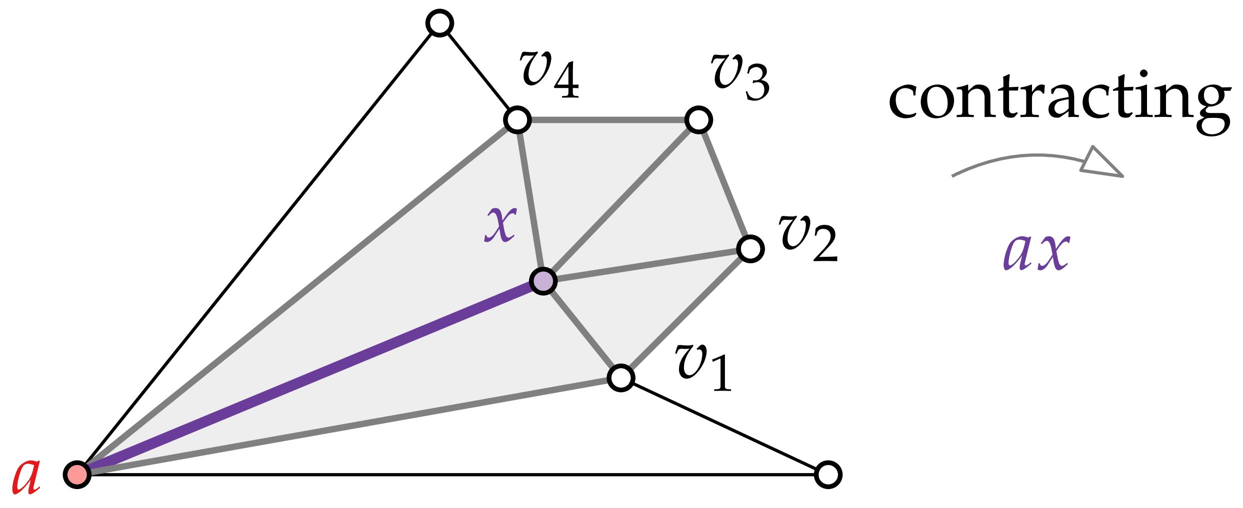

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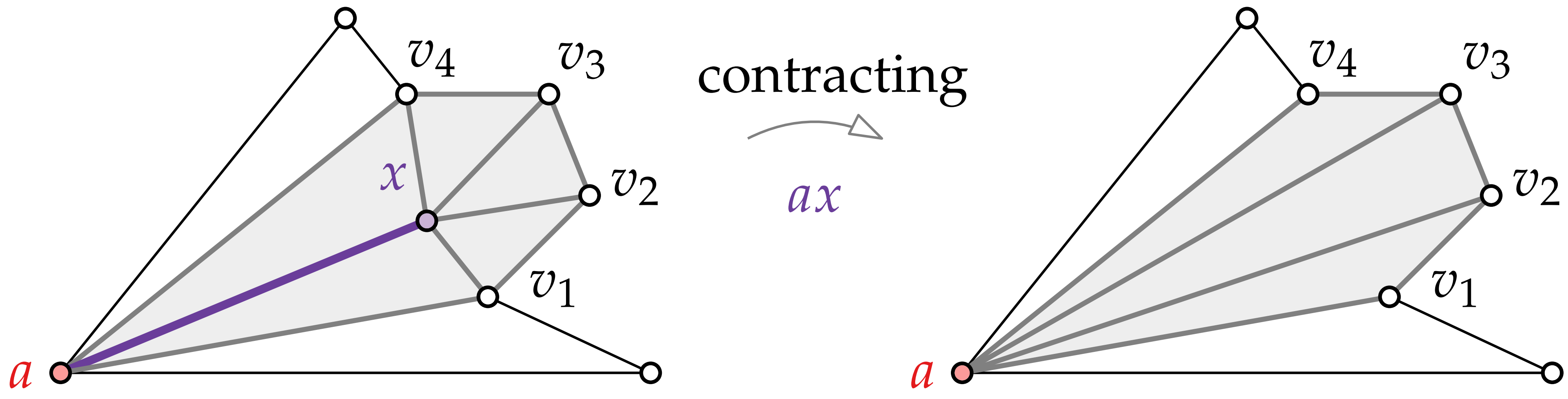

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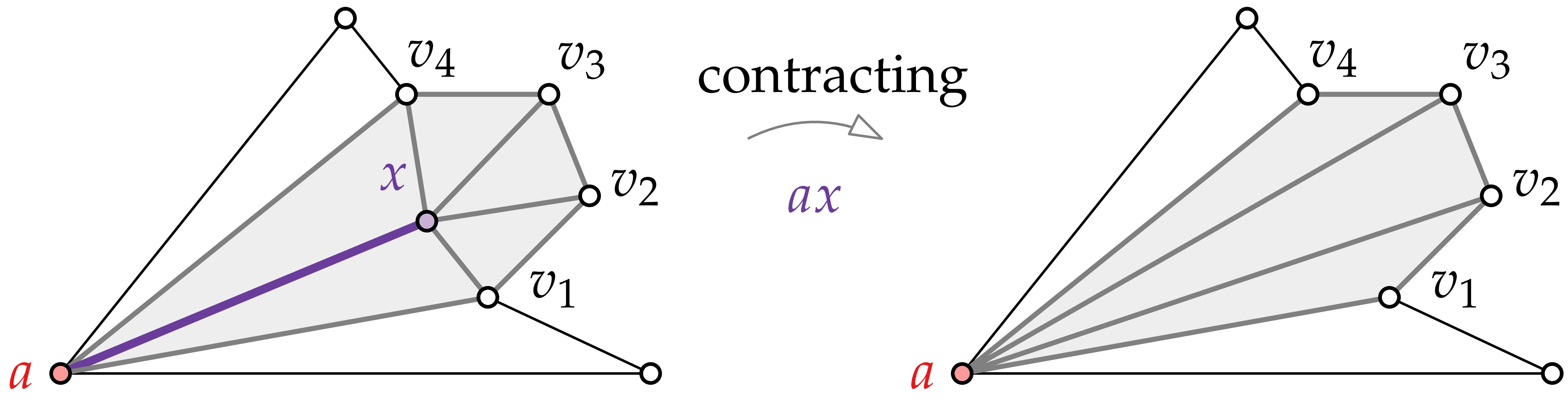

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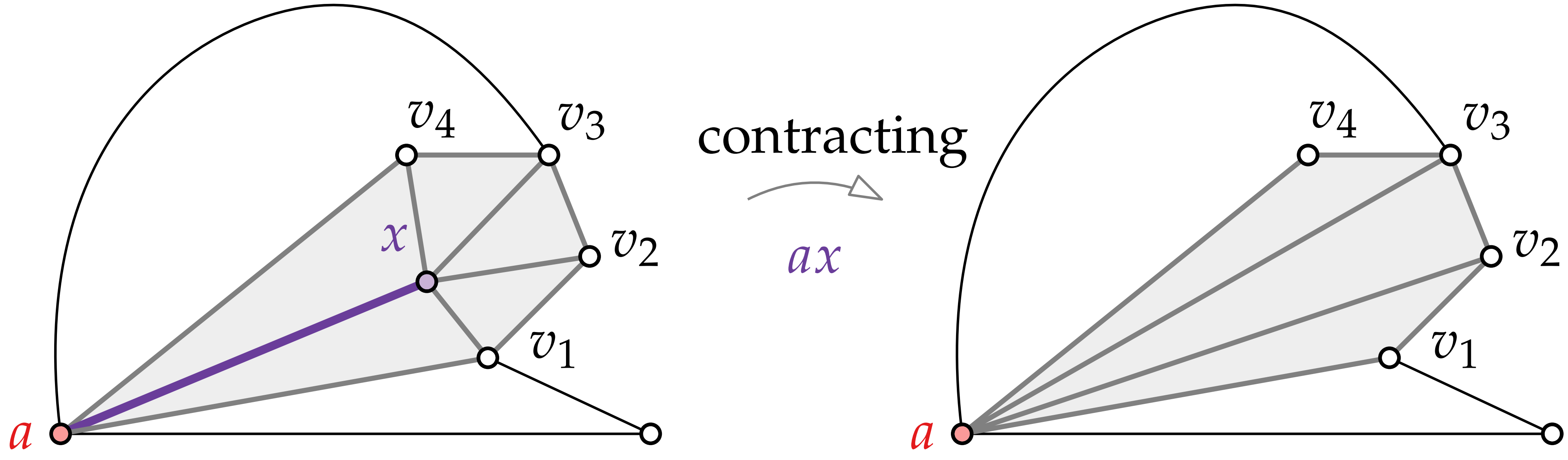

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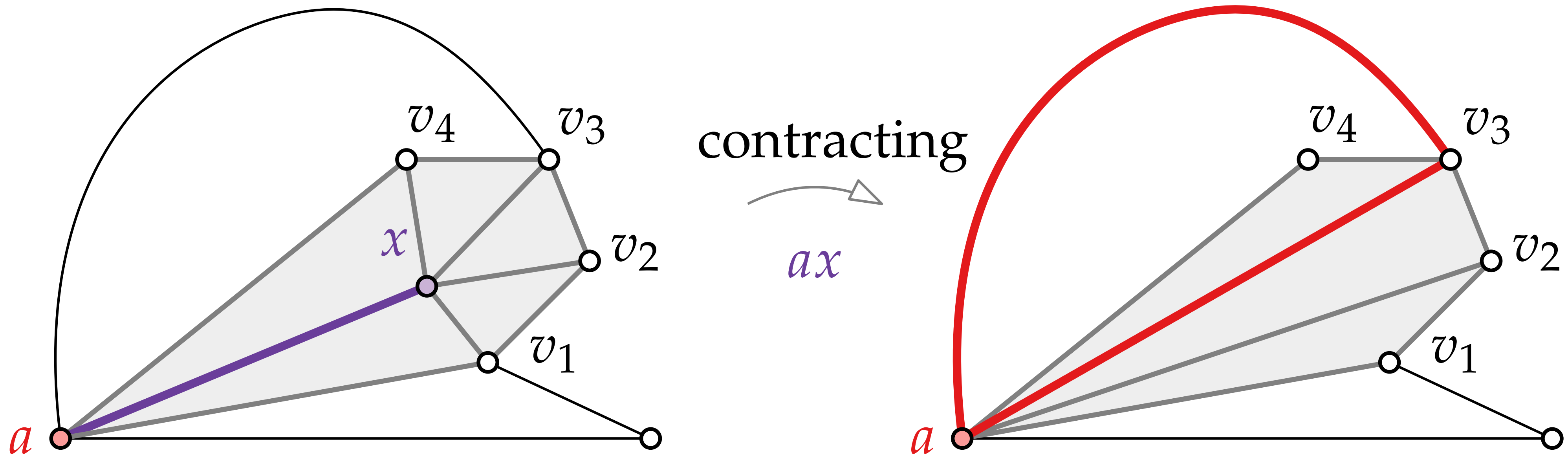

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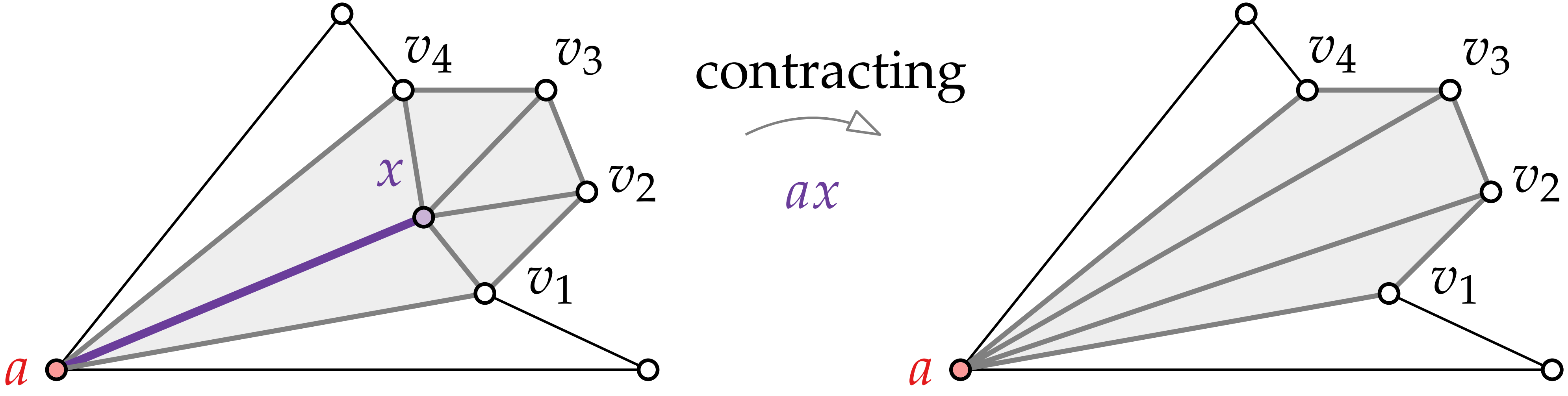

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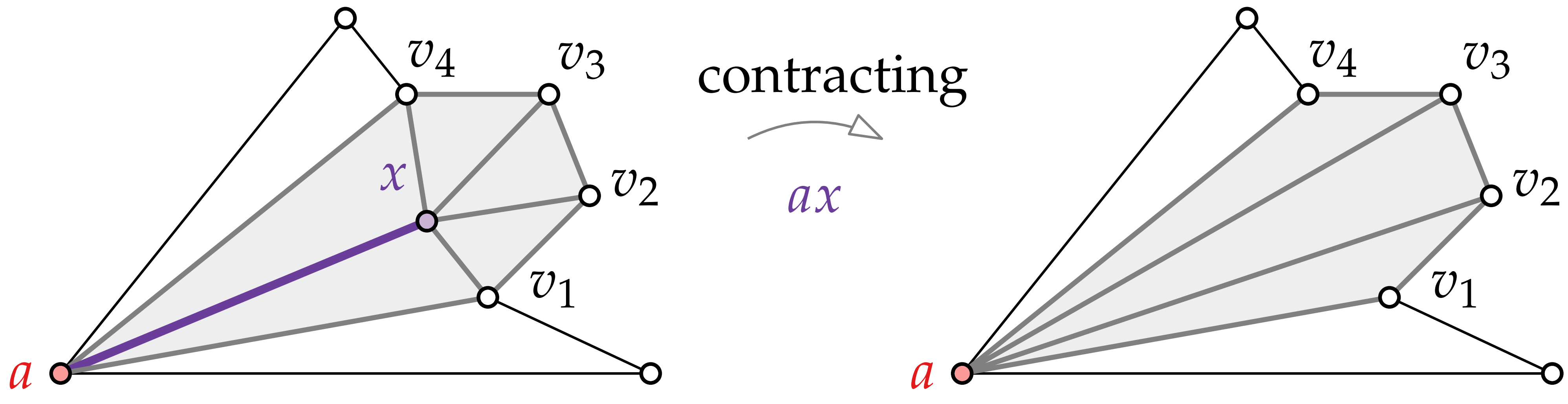

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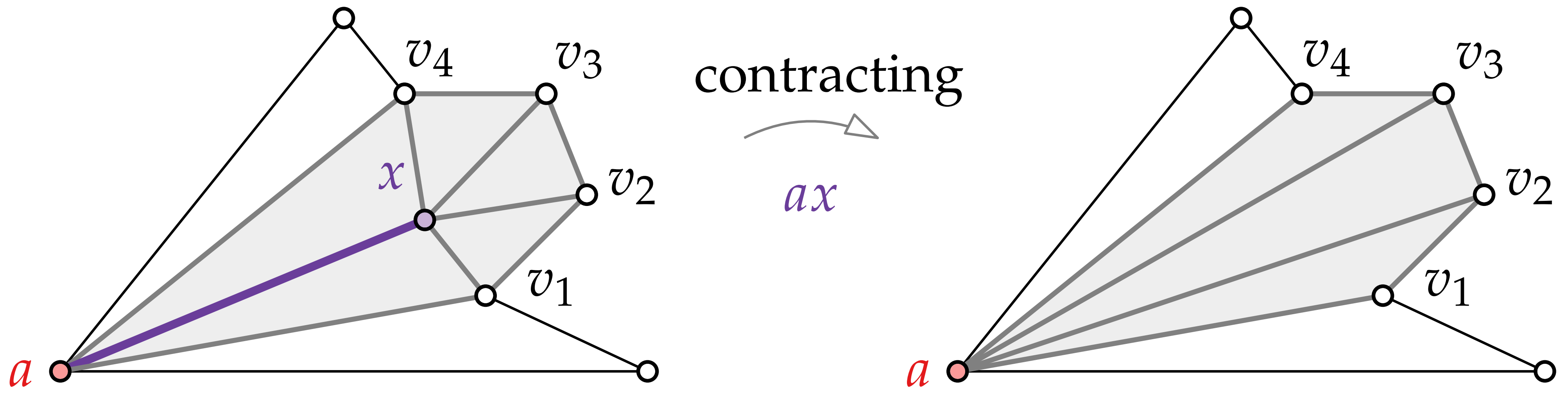

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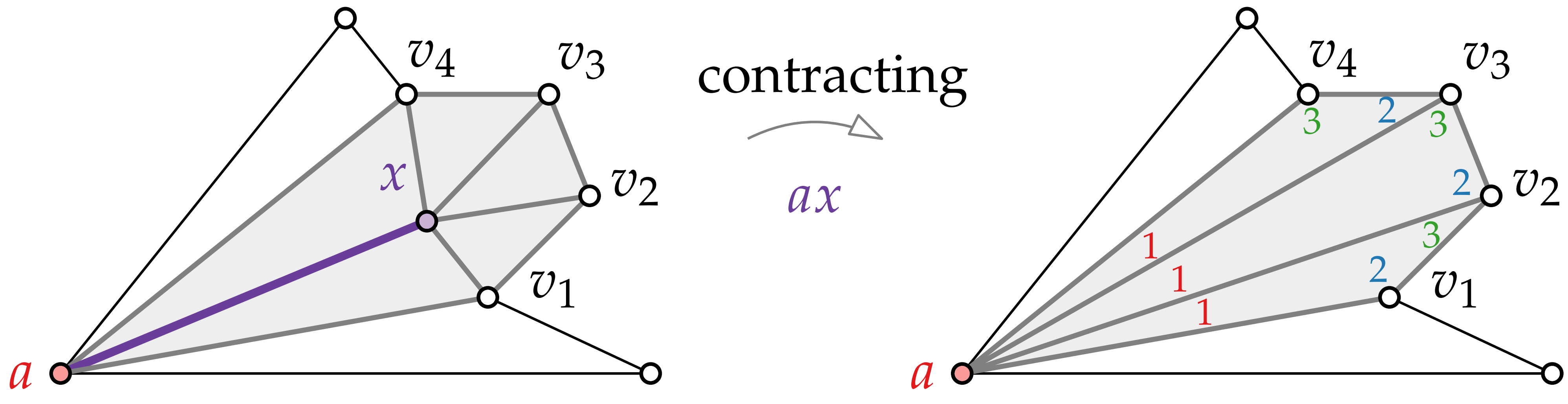

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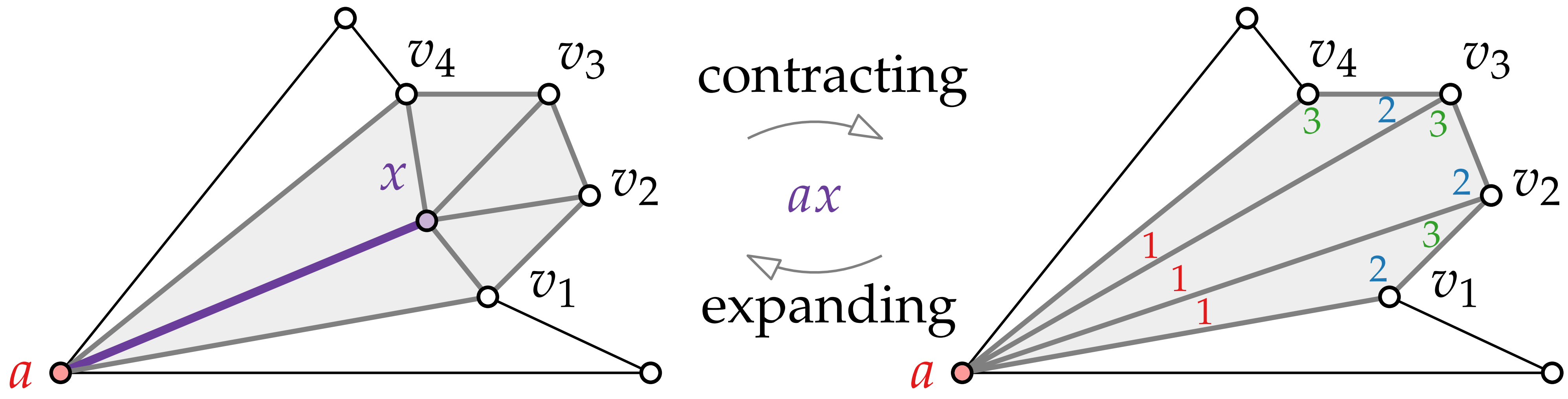

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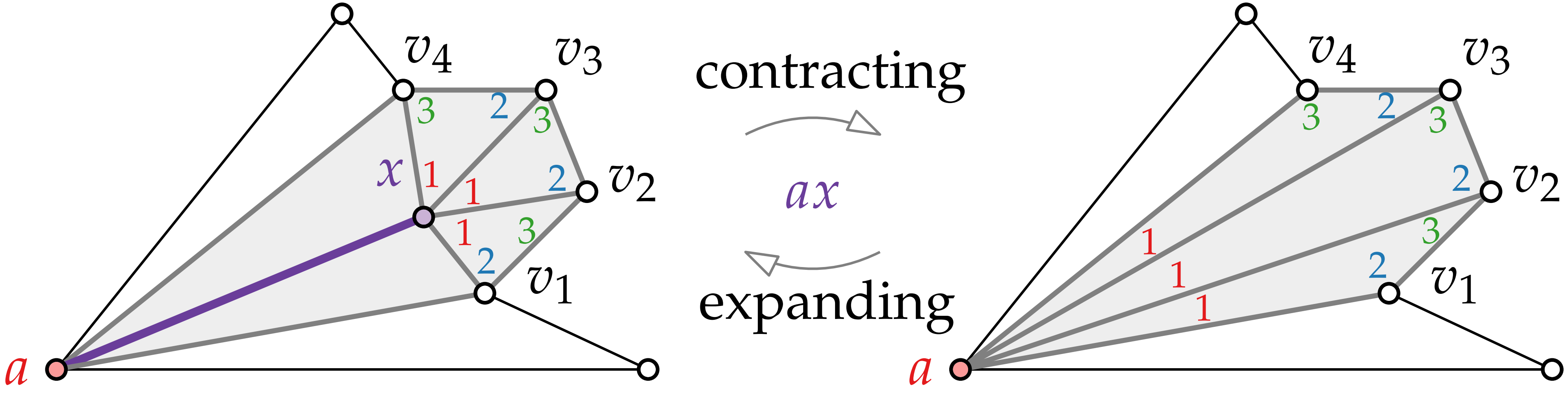

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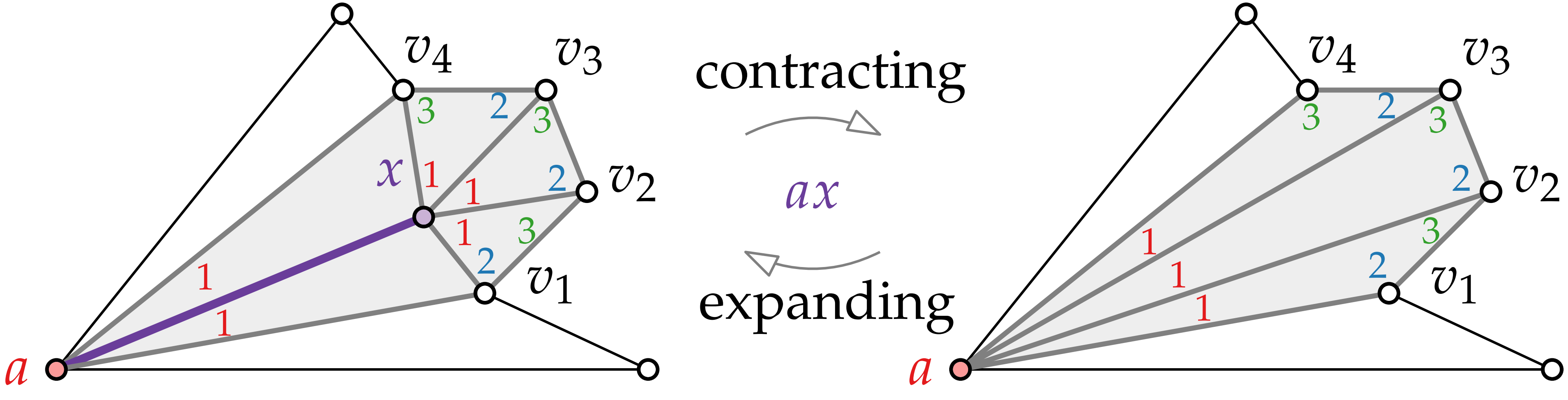

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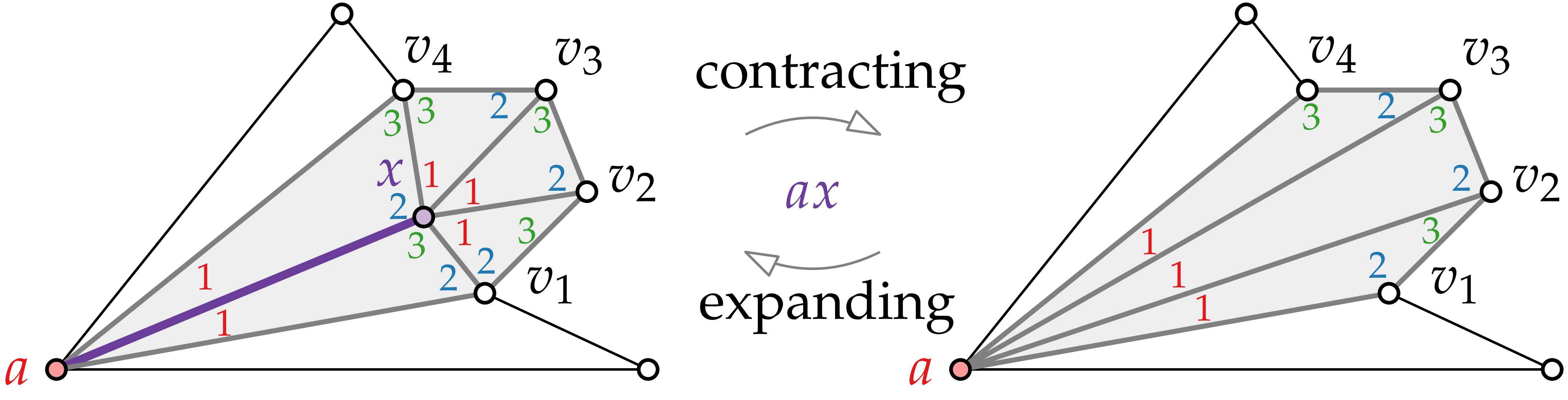

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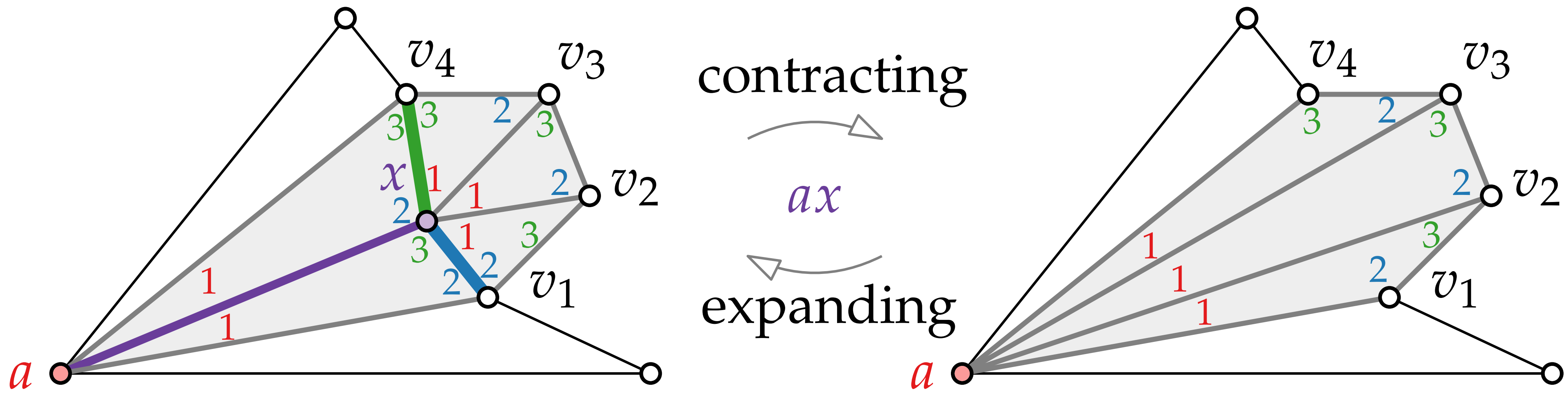

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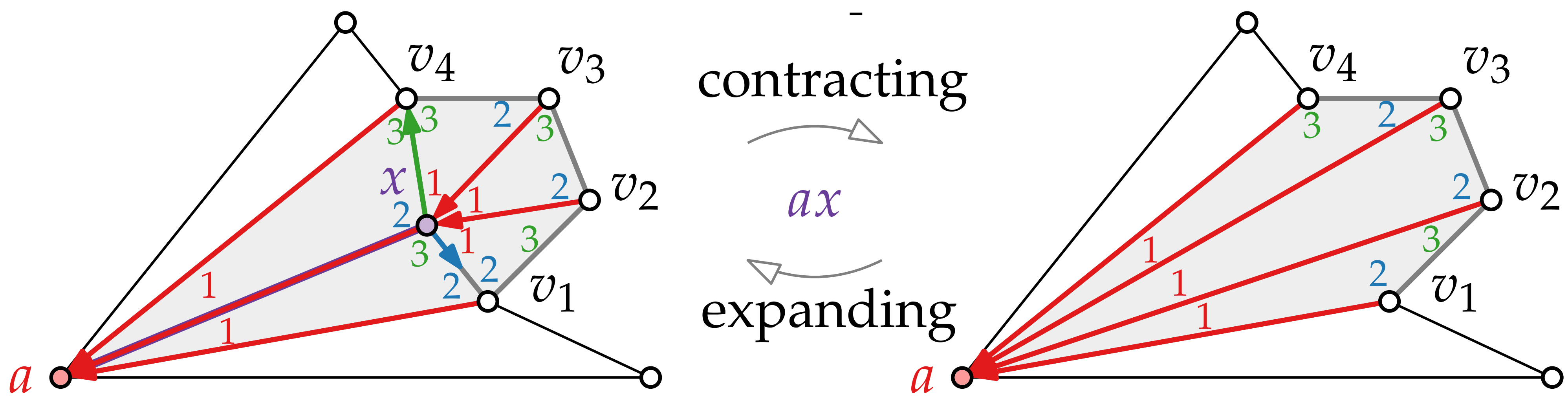

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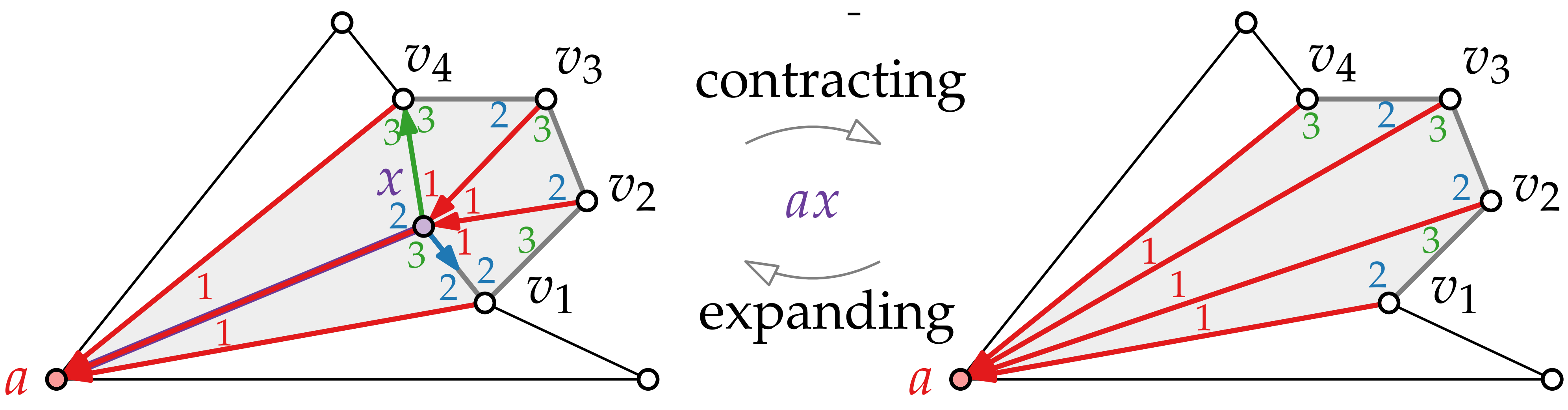

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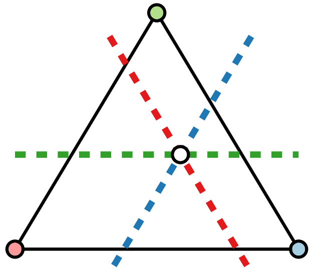
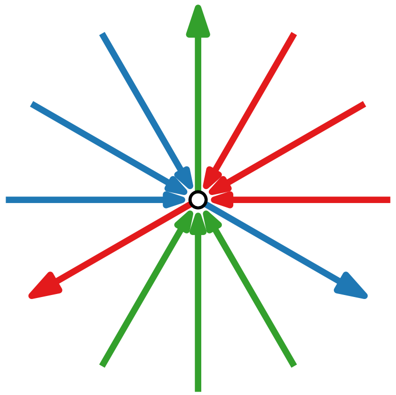
Constructive proof can be used as algorithm to compute a Schnyder labeling. It can be implemented in $\mathcal{O}(n)$ time … as exercise.

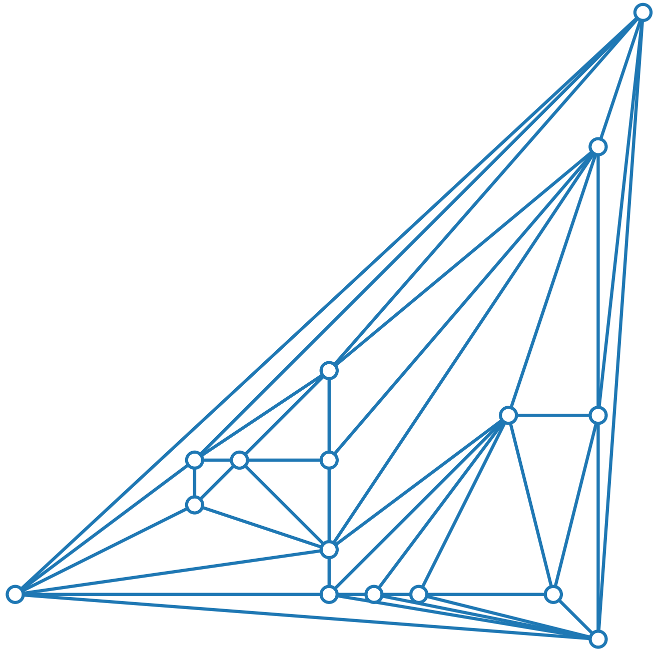
Universität Trier



Visualization of Graphs



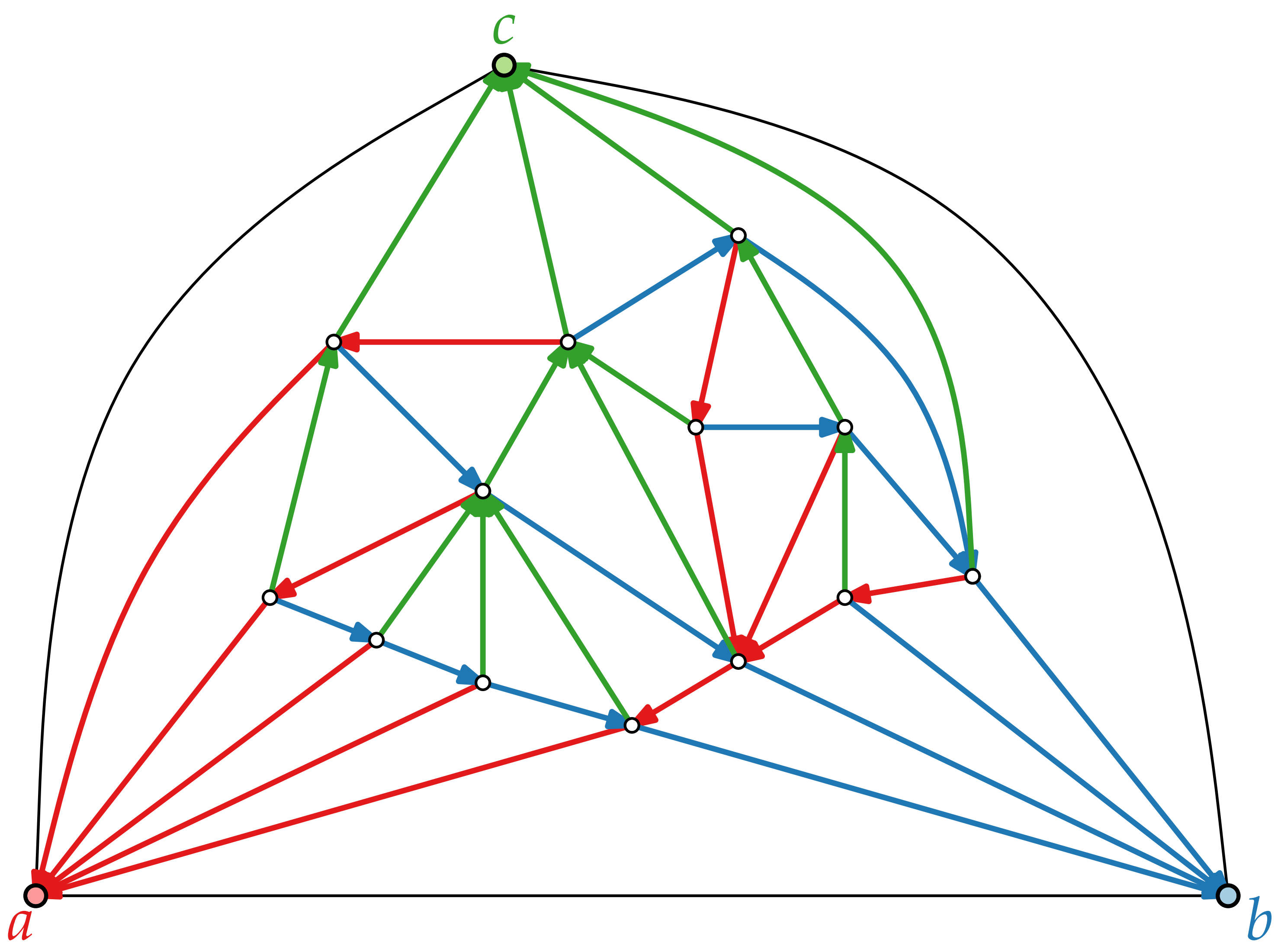
Lecture 5:
Straight-Line Drawings of Planar Graphs II:
Schnyder Realizer



Part III:
Schnyder Drawings

Philipp Kindermann

Schnyder Realizer – More Properties



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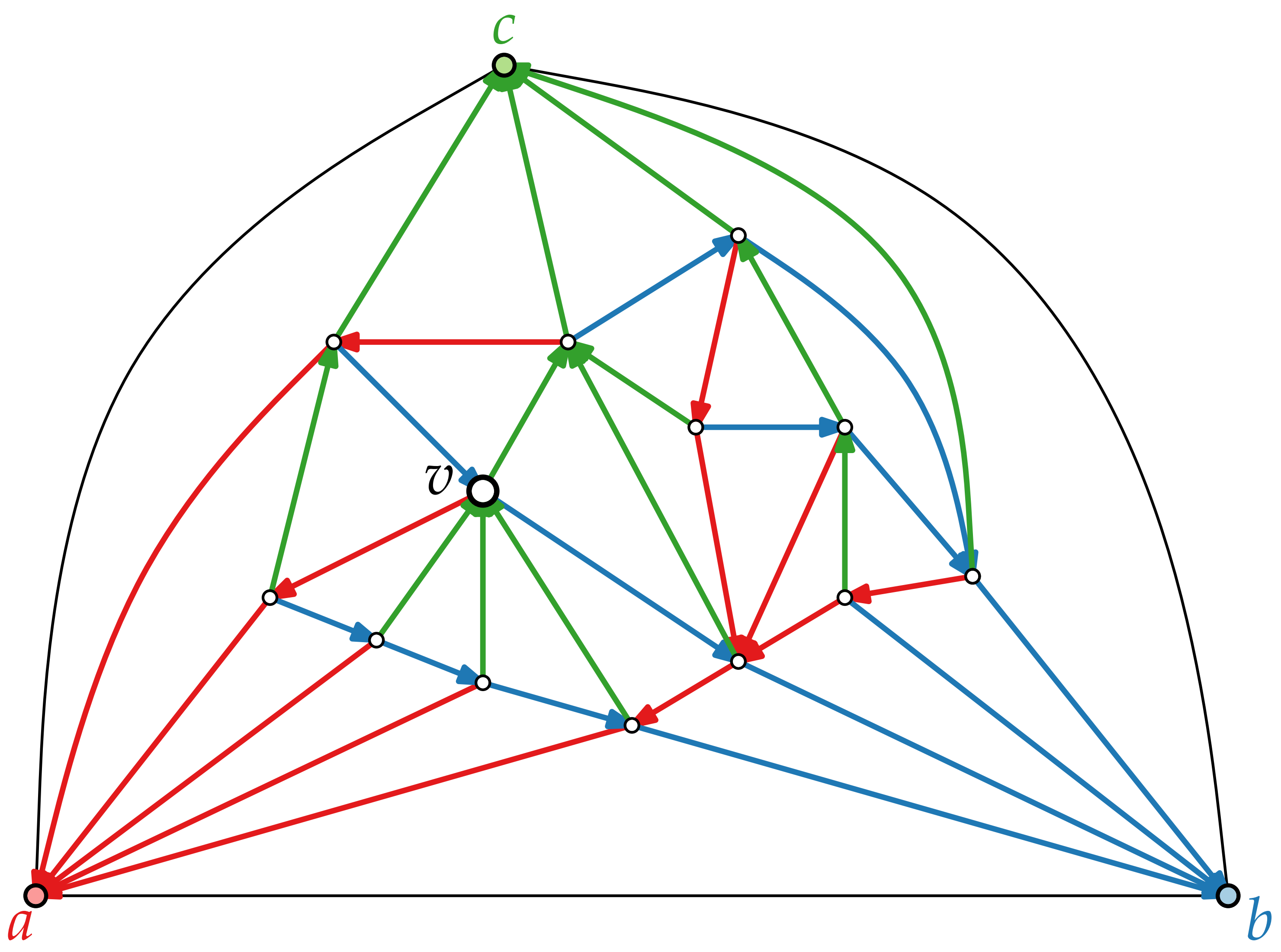

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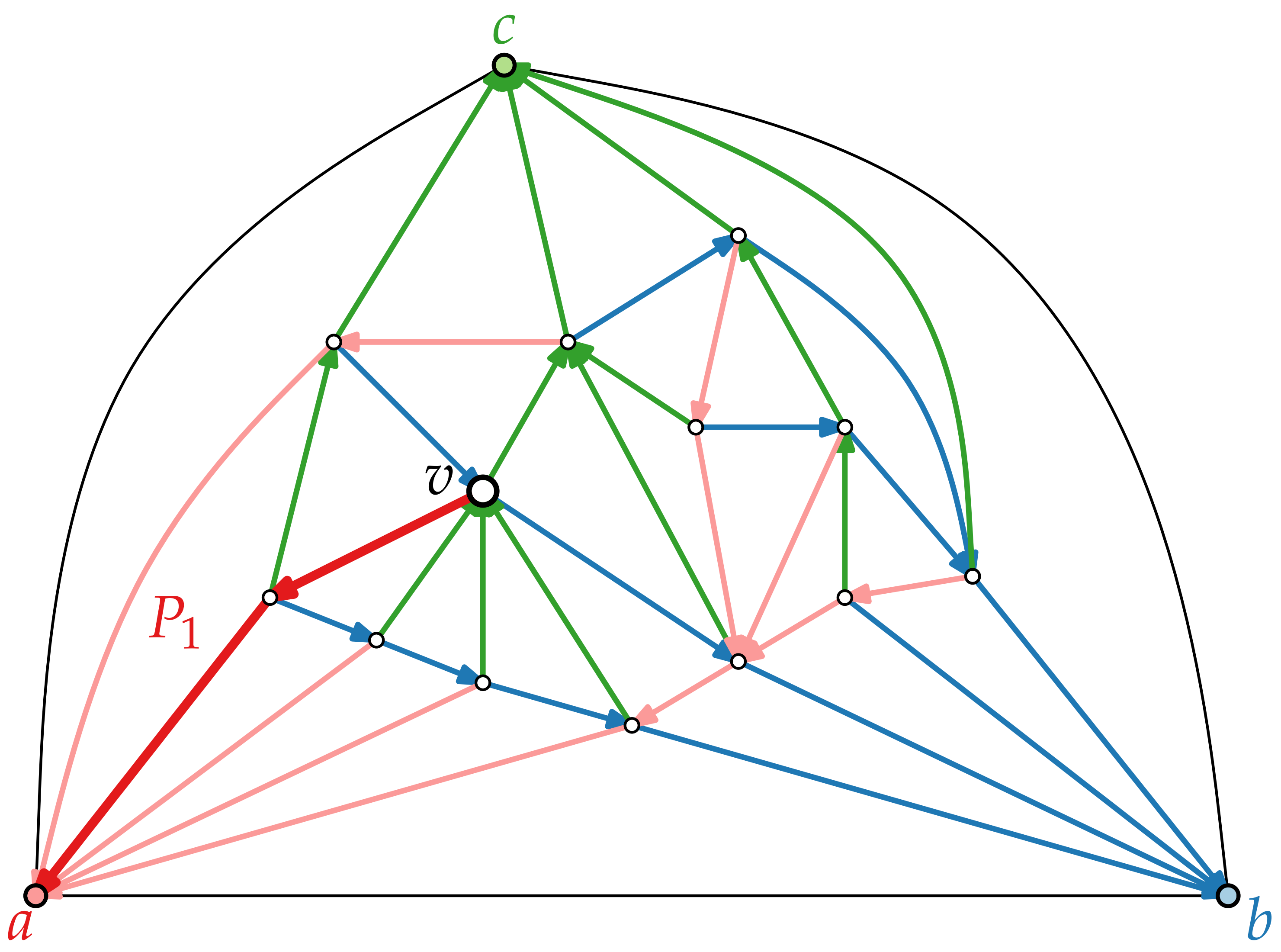
Schnyder Realizer – More Properties



- From each vertex v there exists a directed red path $P_1(v)$ to a,

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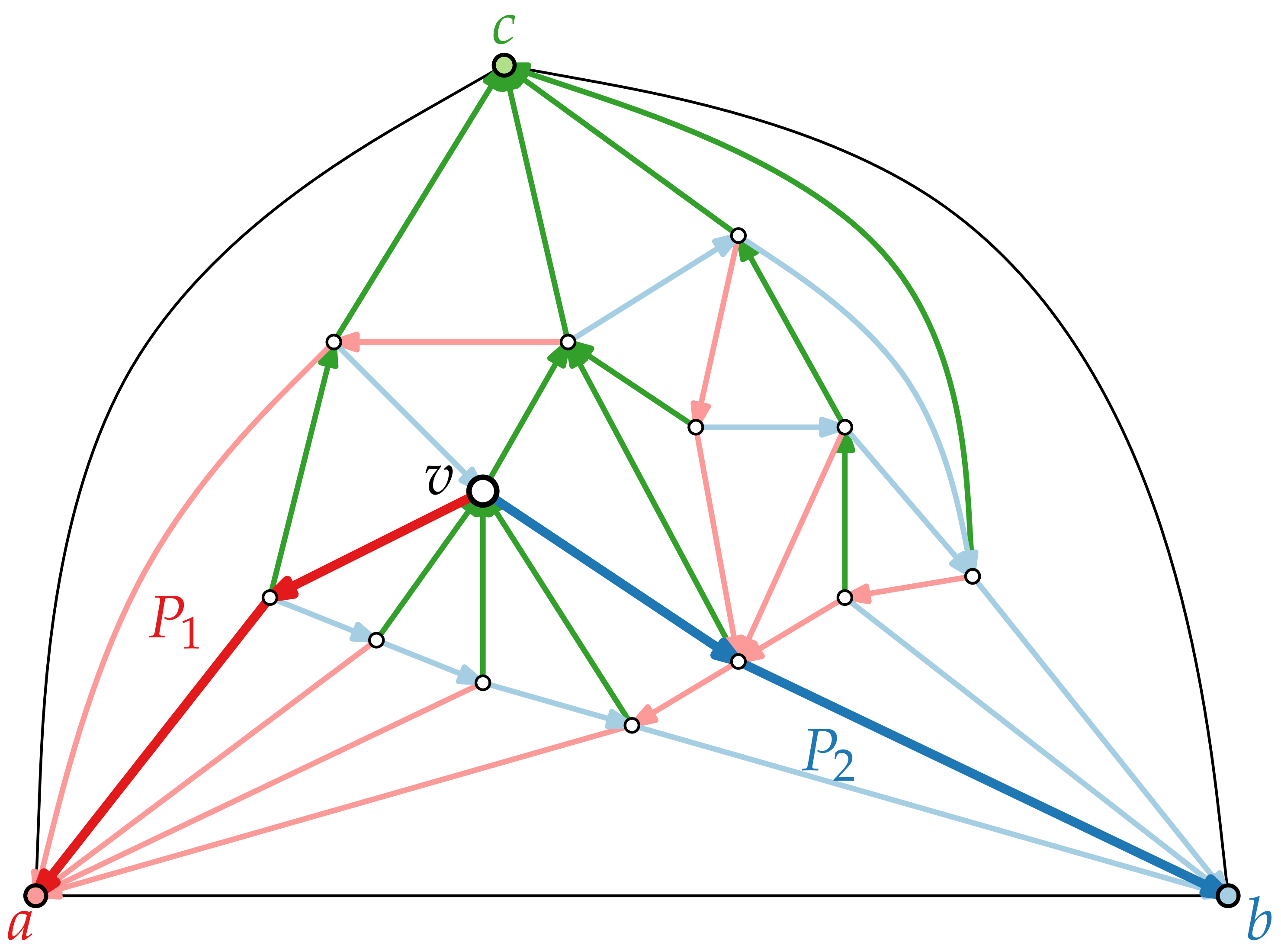

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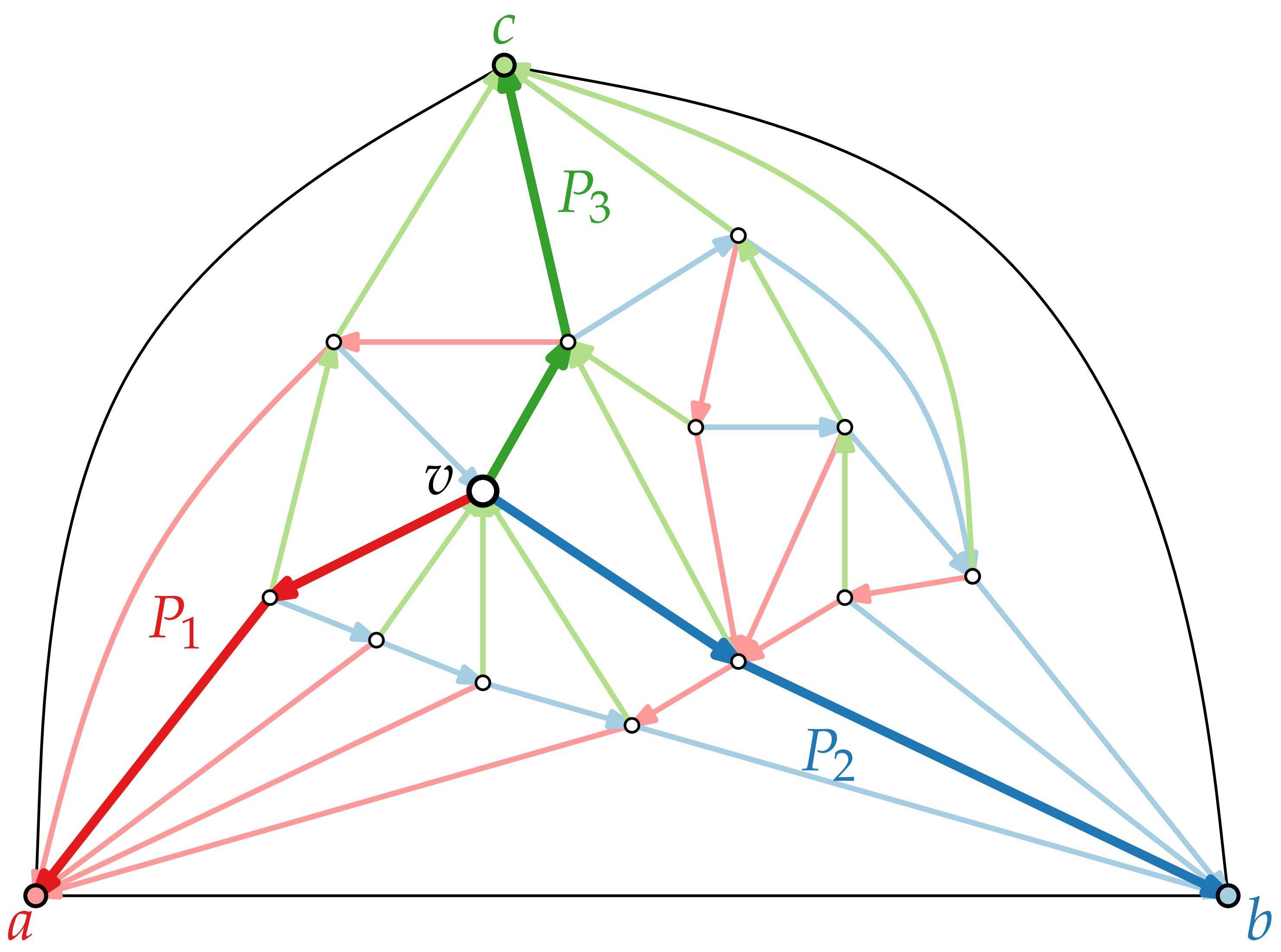

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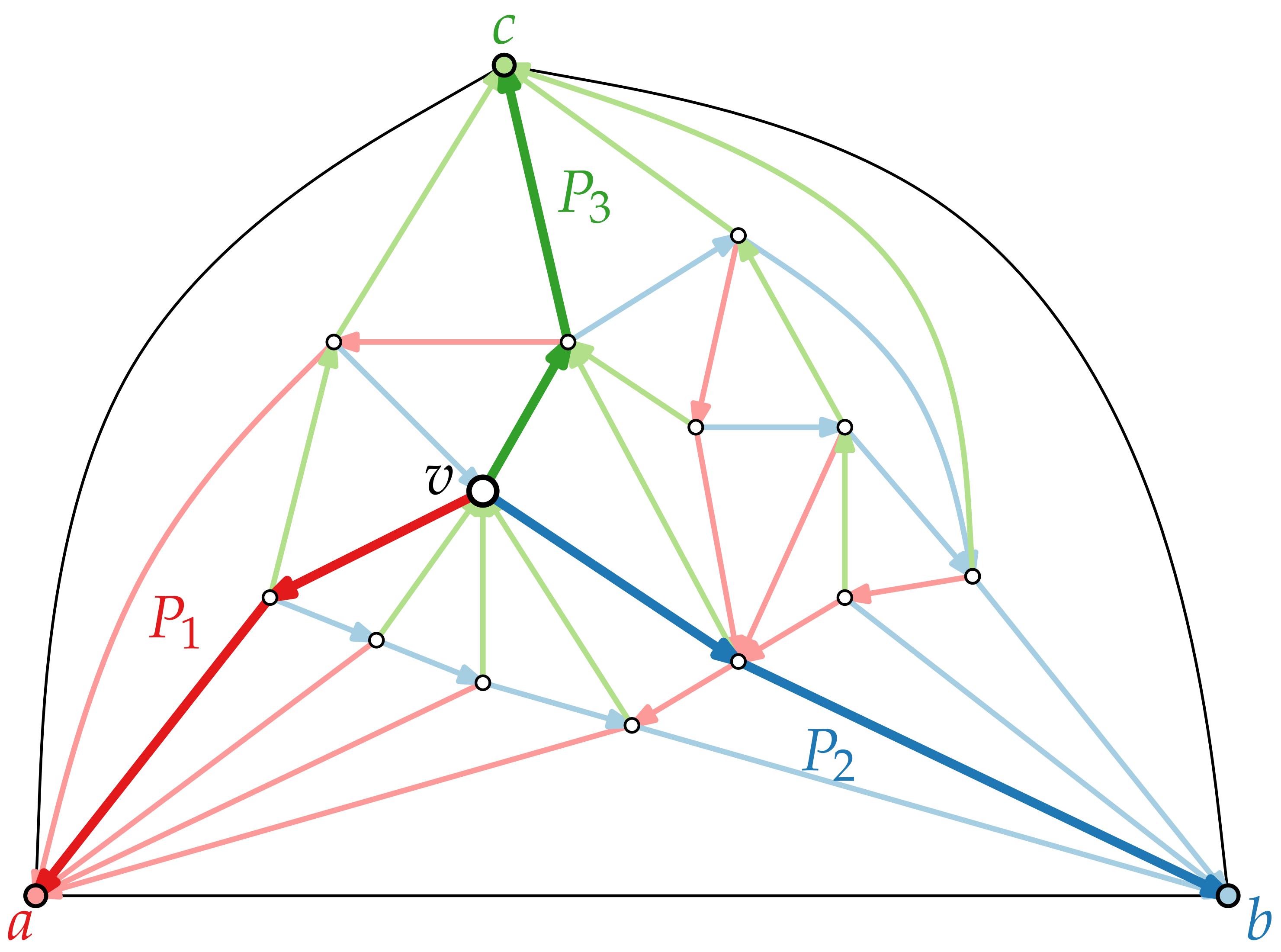

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$P_i(v)$: path from v to root of T_i.

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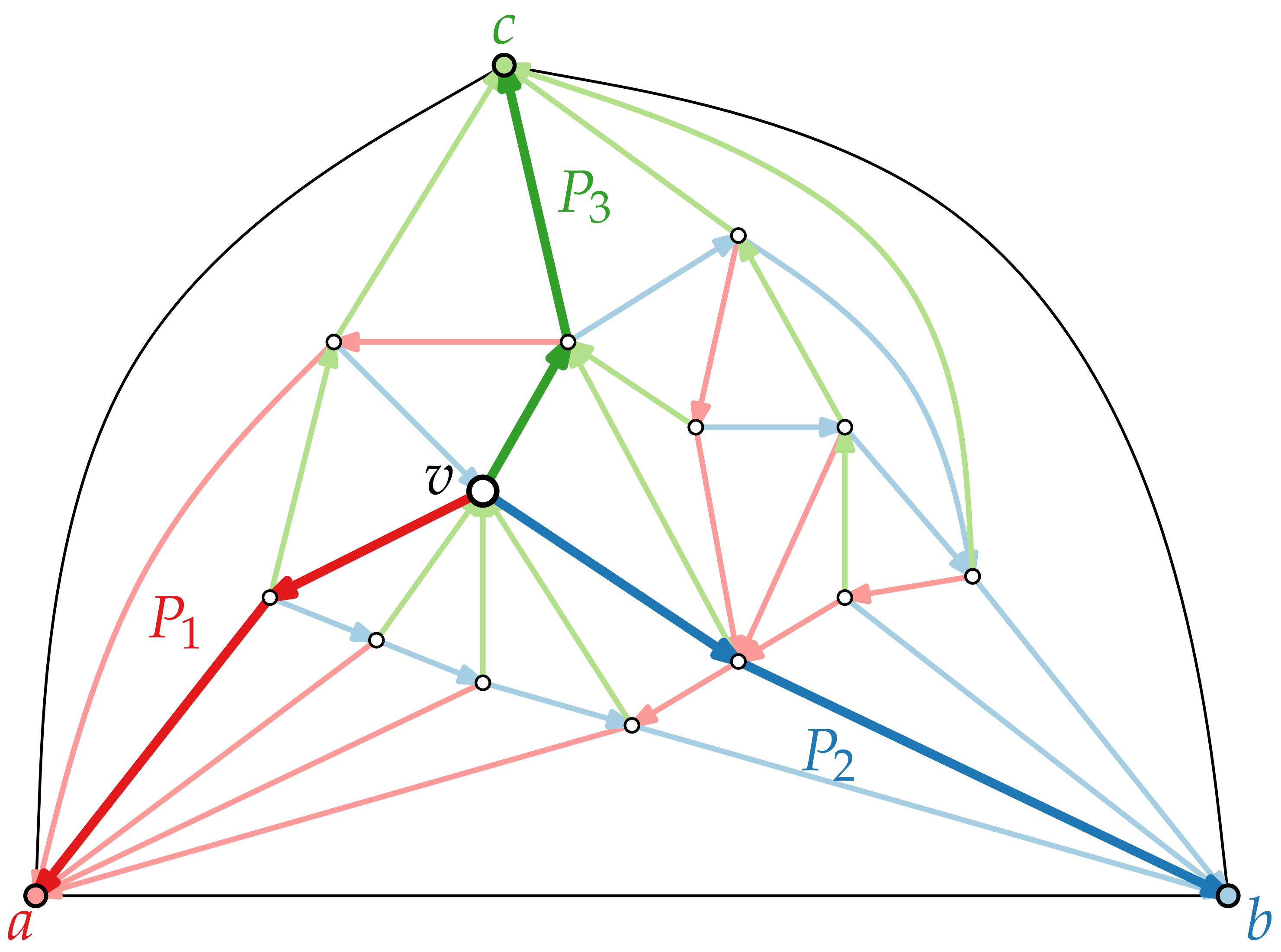

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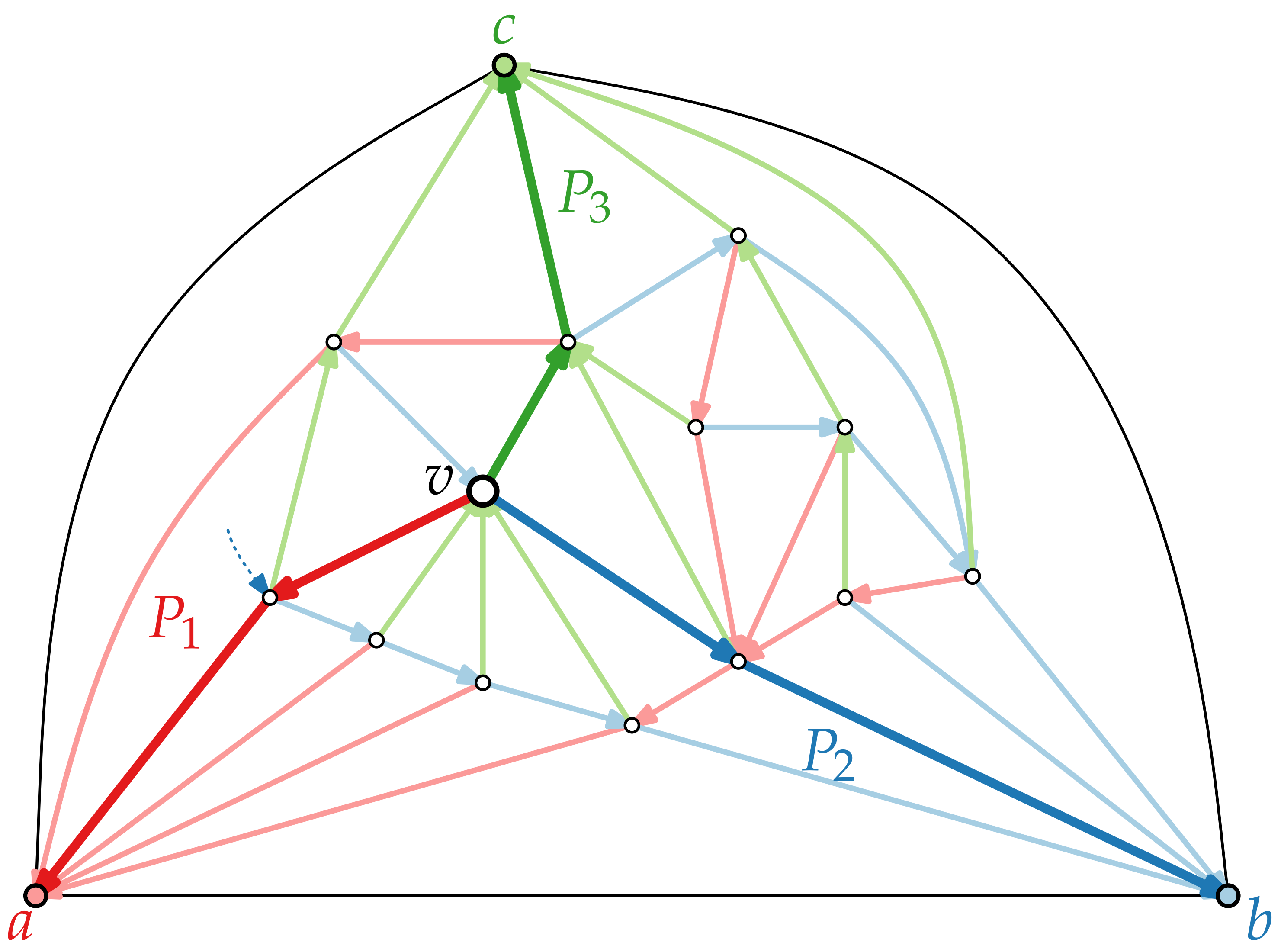

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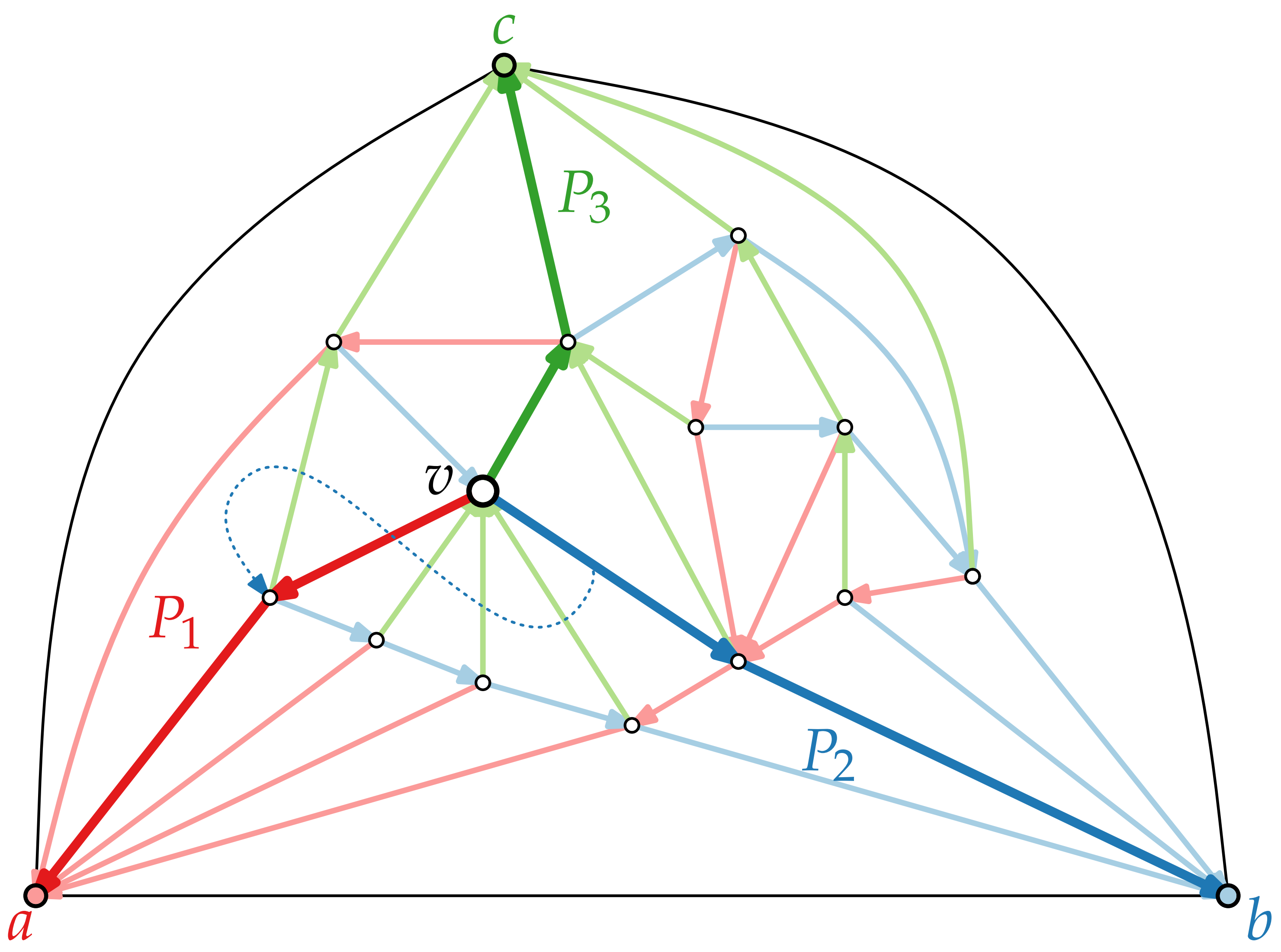

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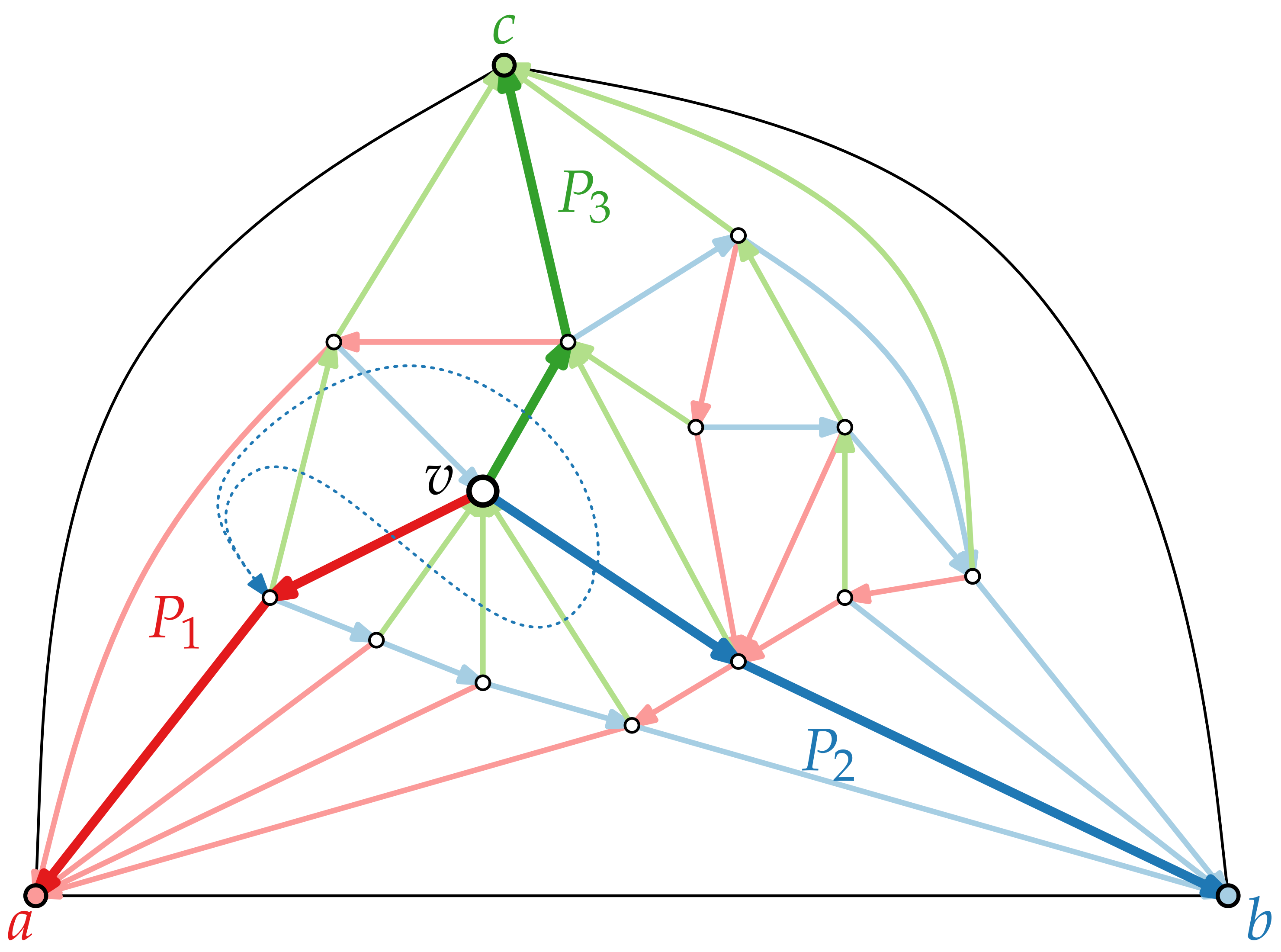

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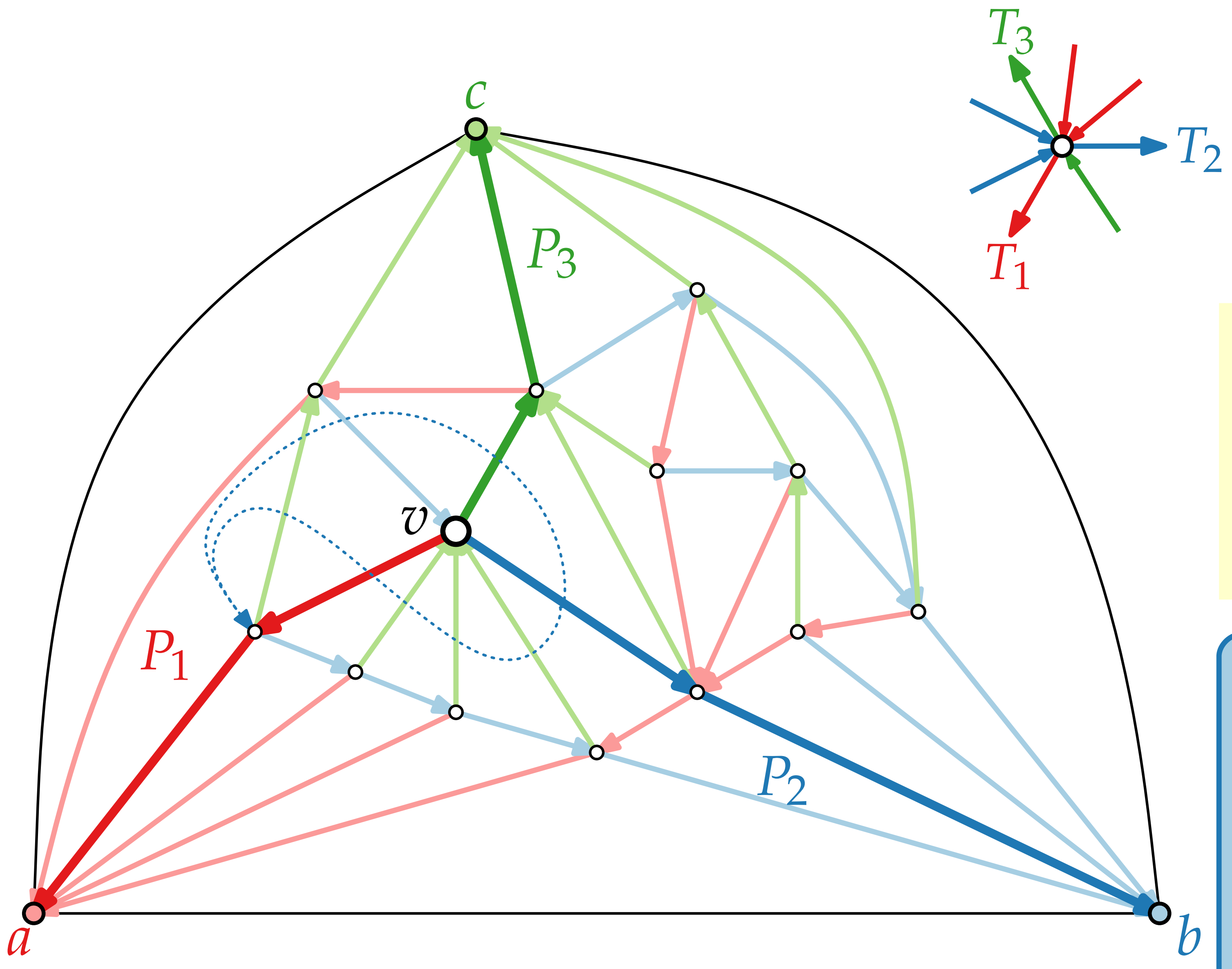

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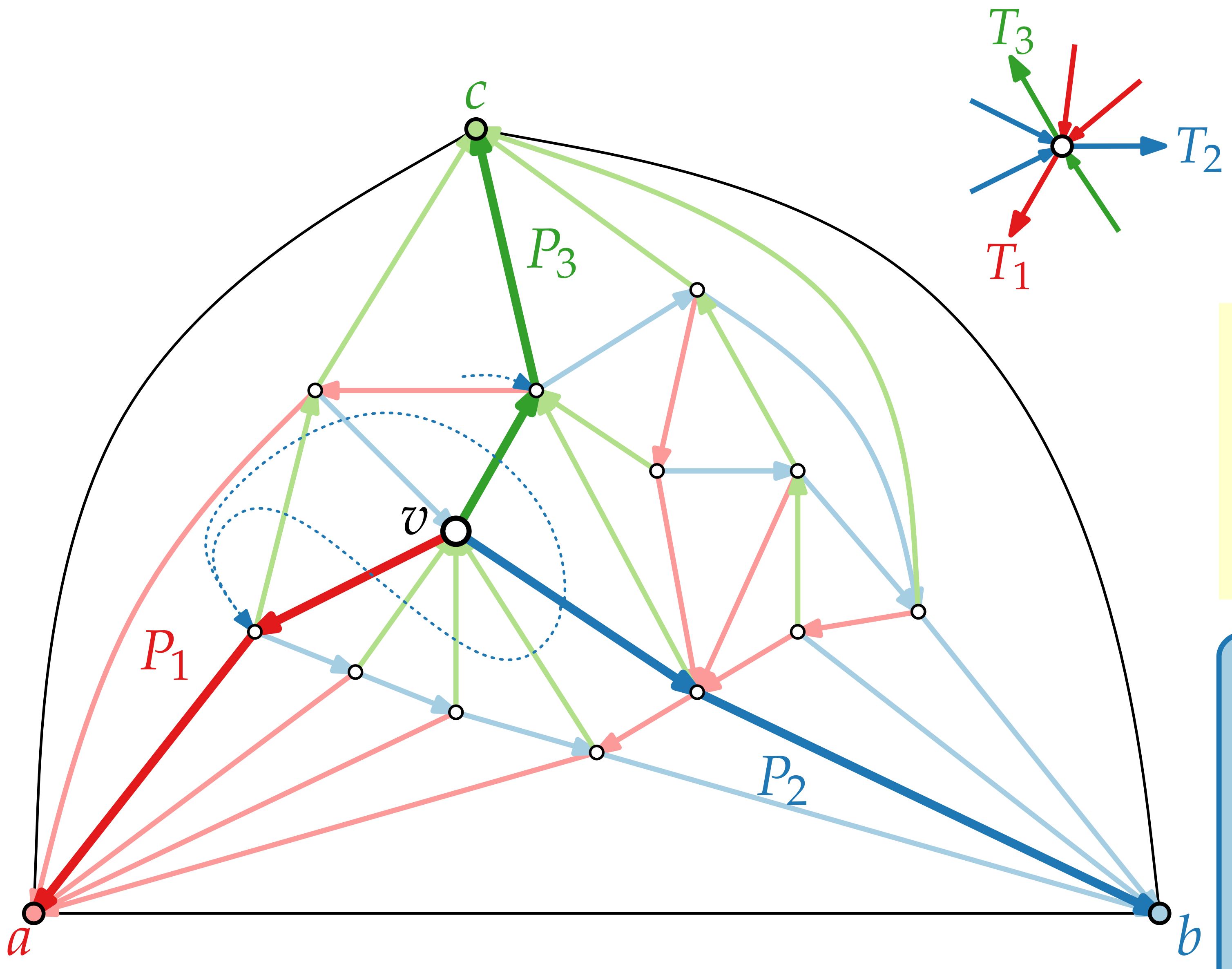

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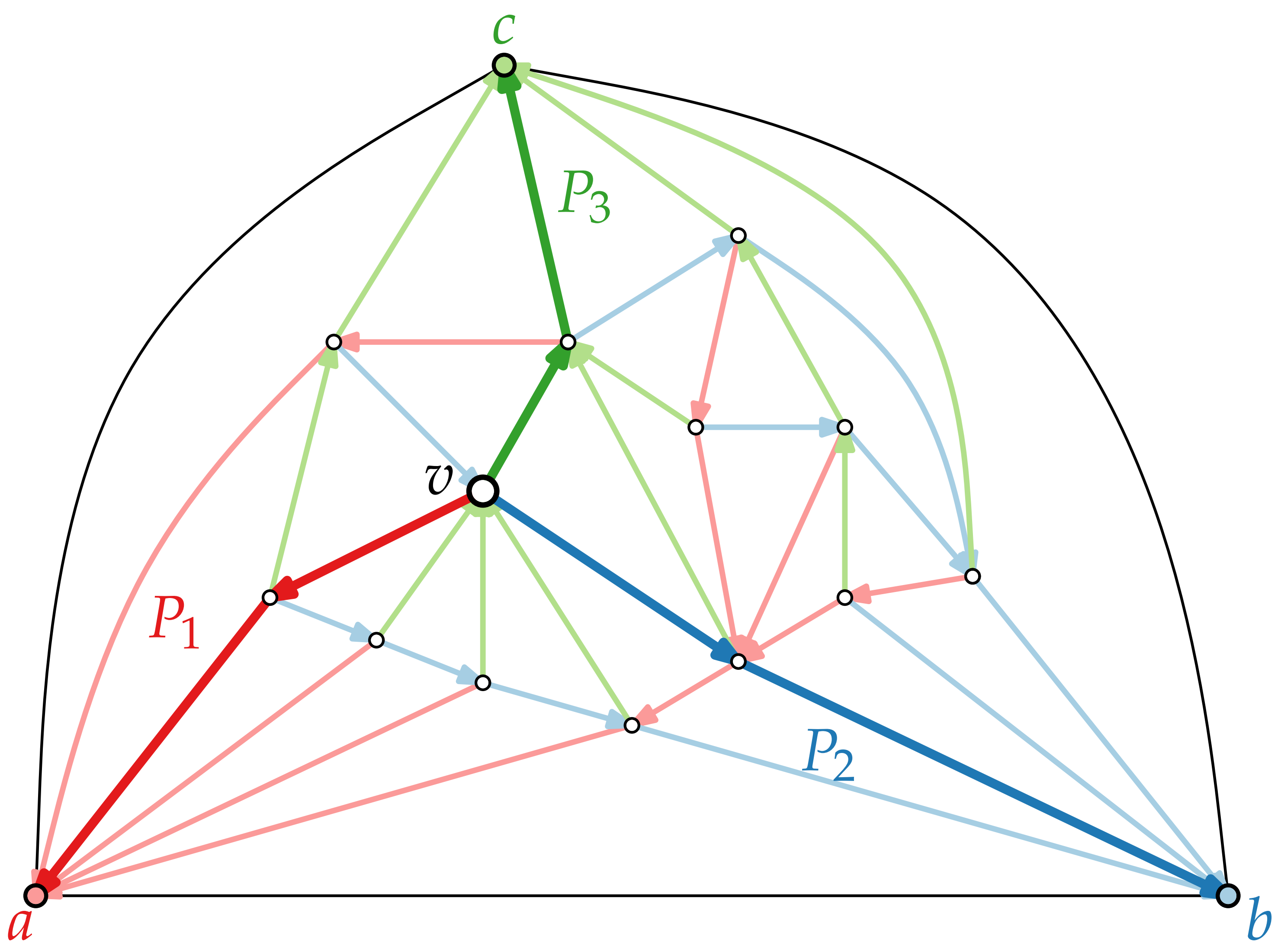

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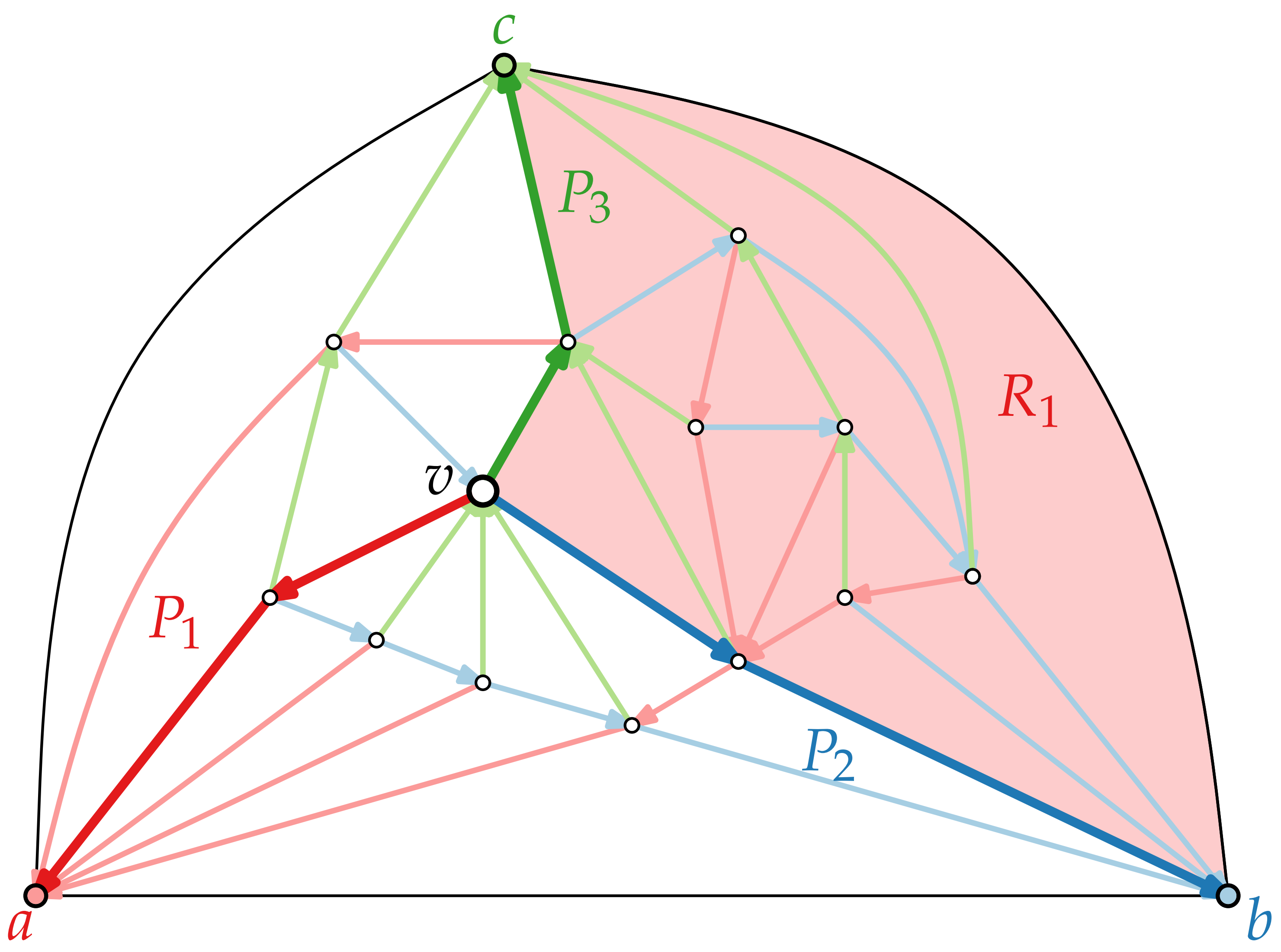

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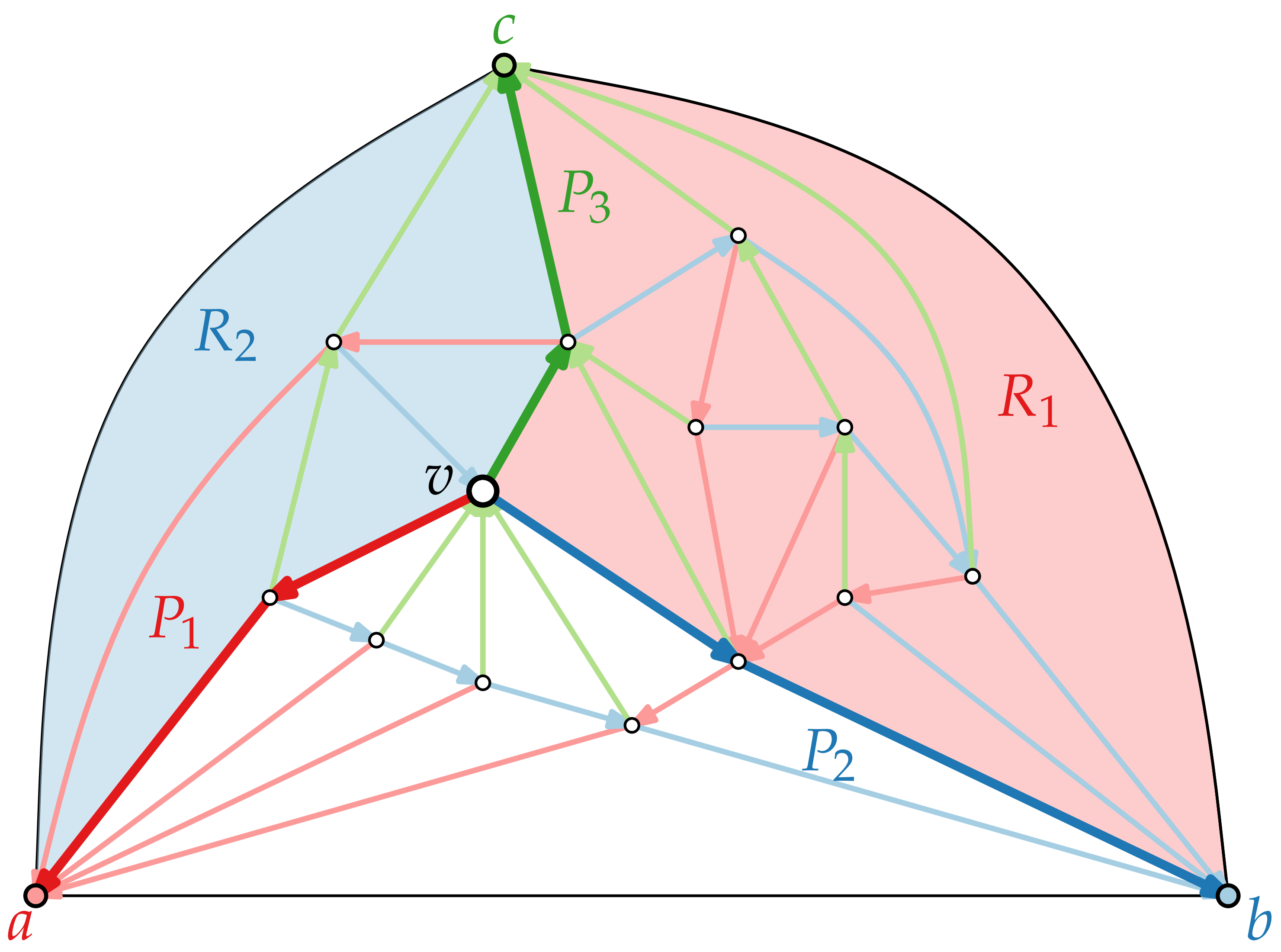

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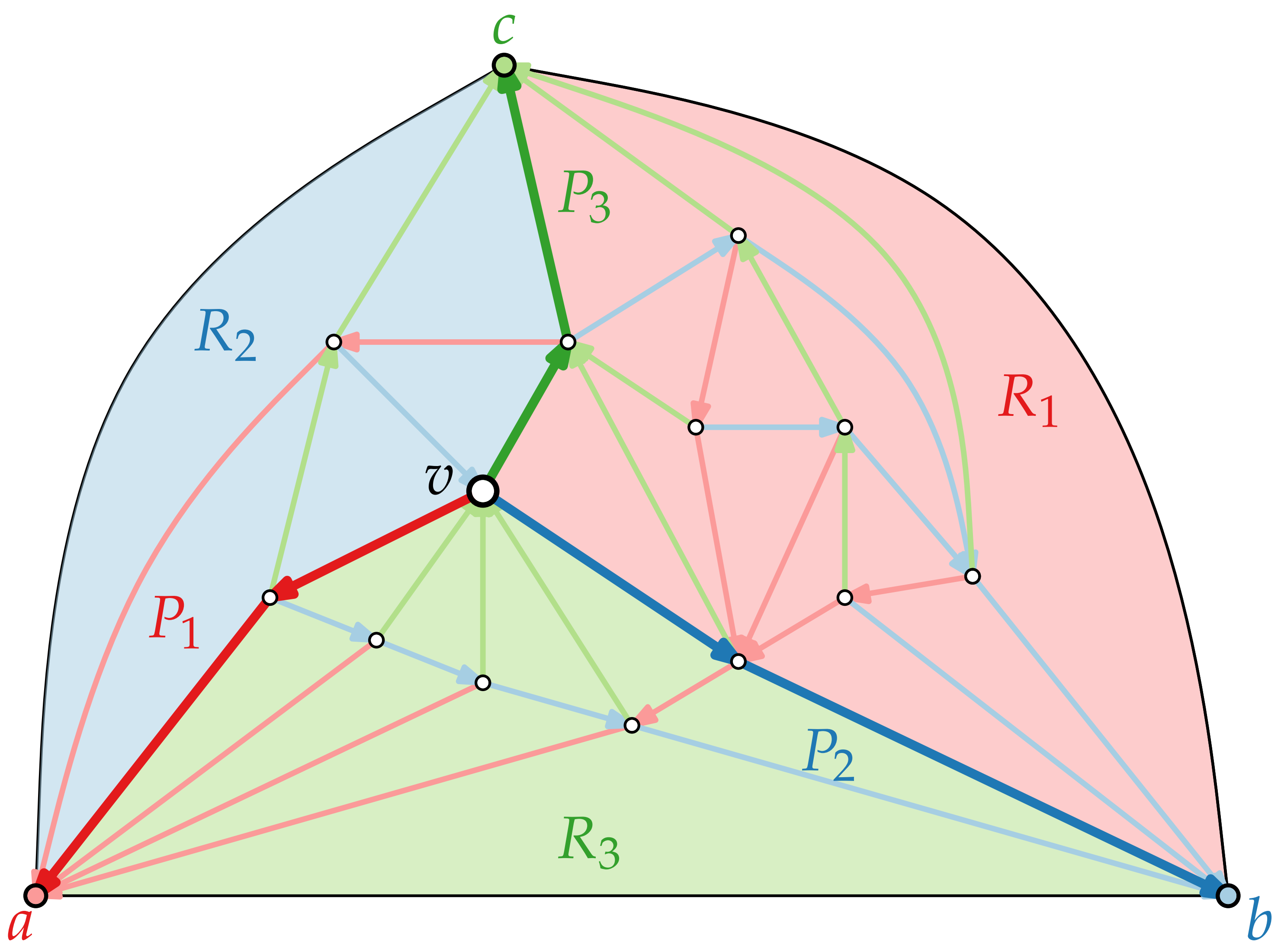

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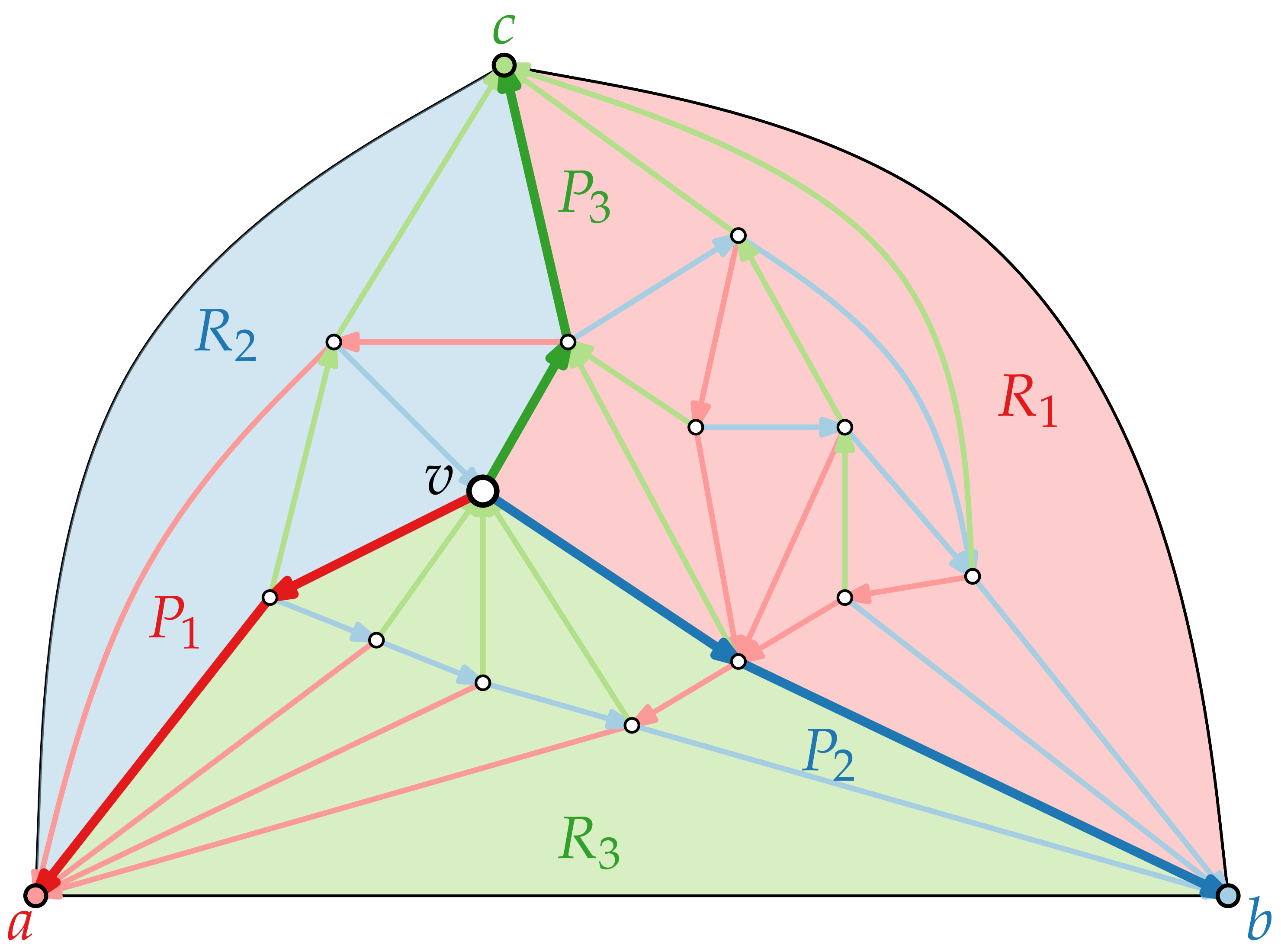

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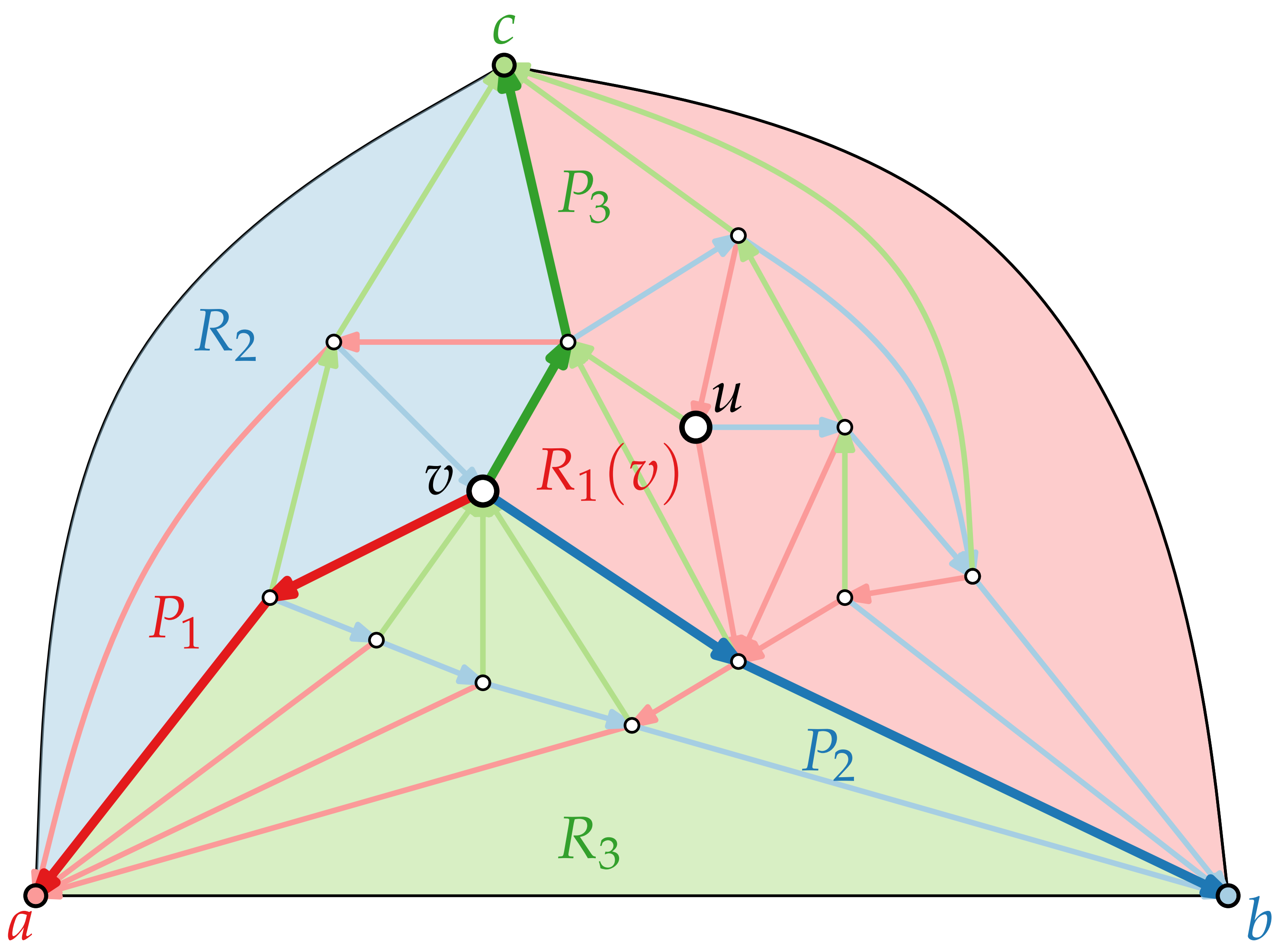

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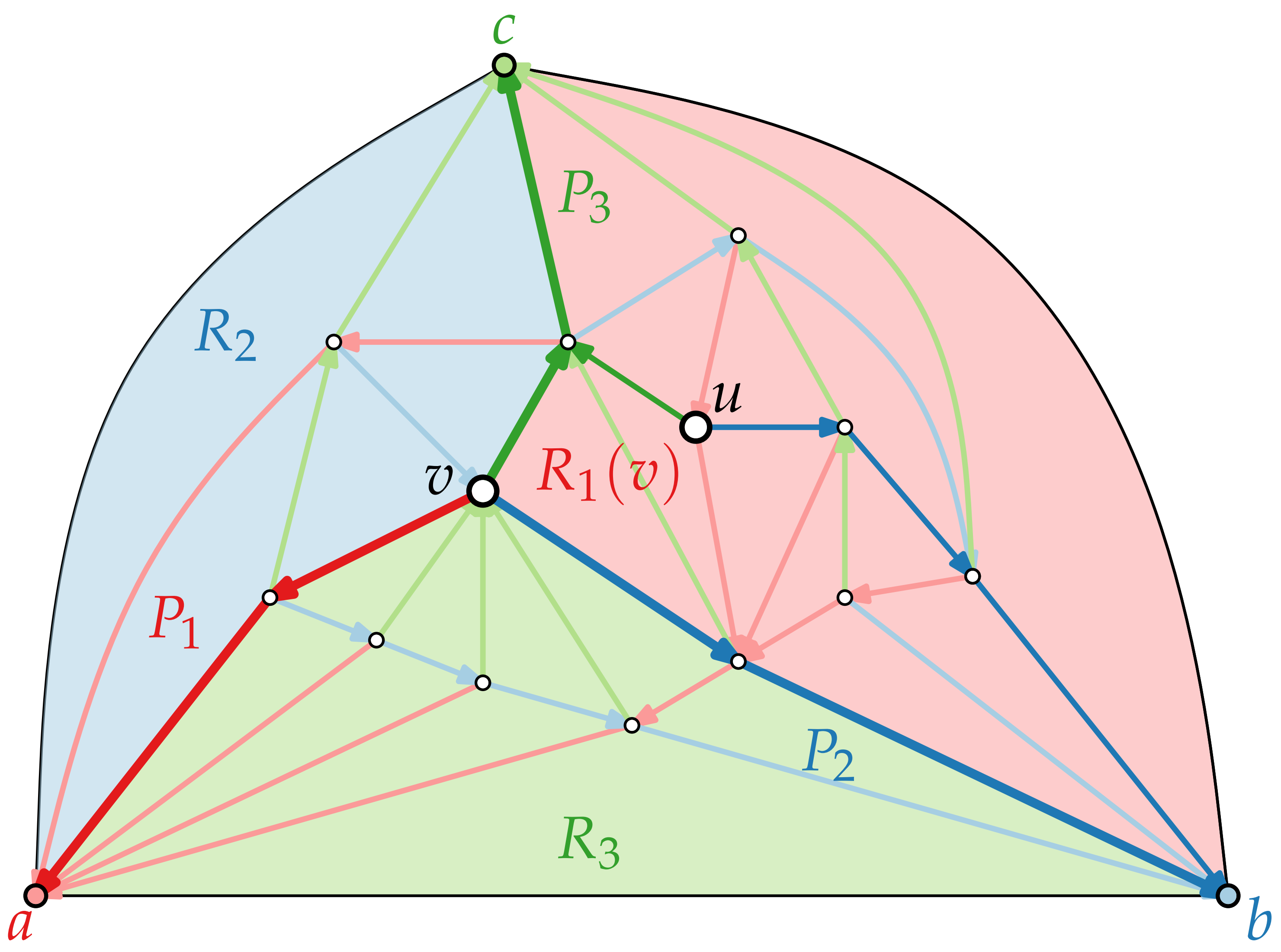

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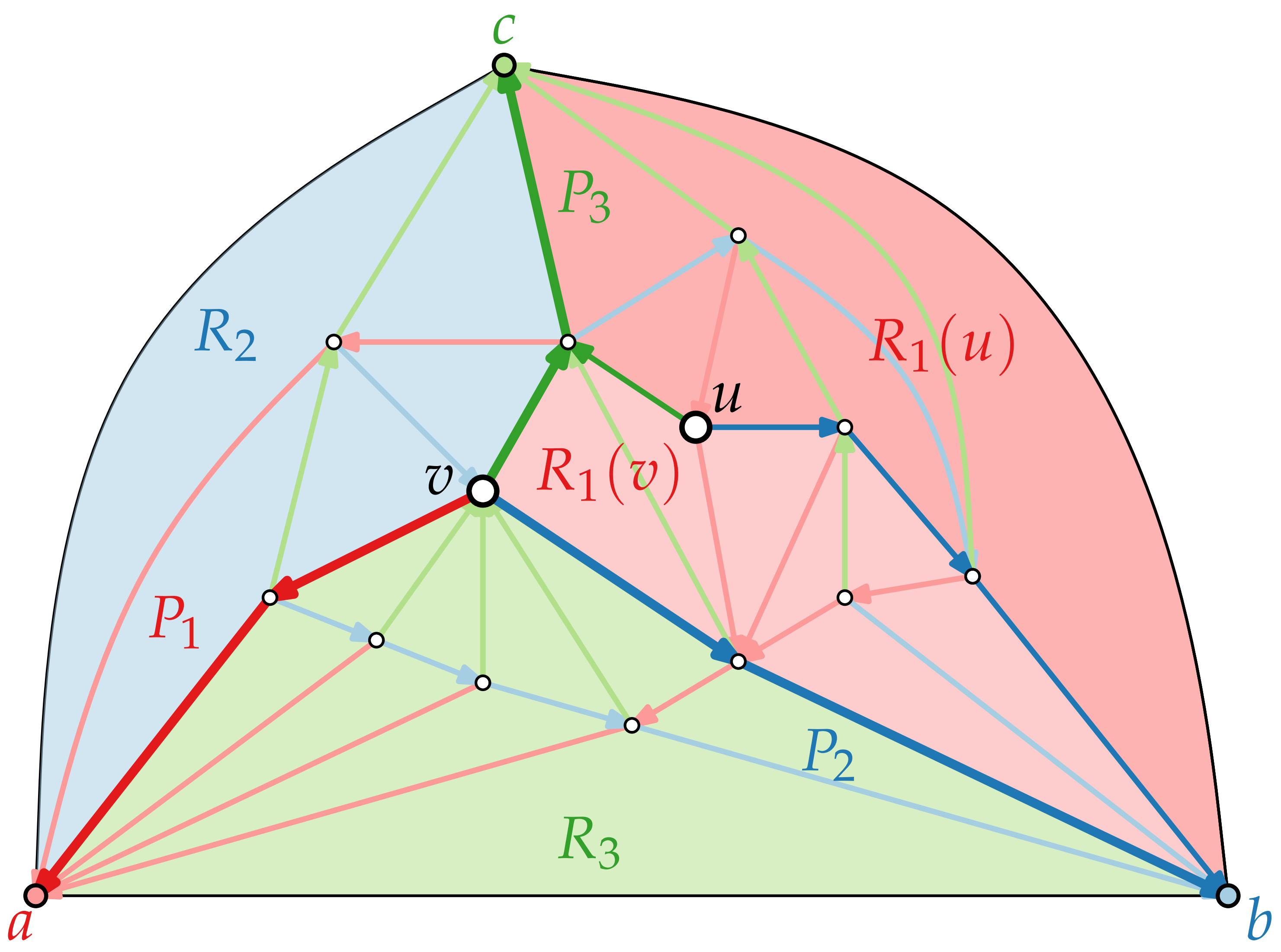

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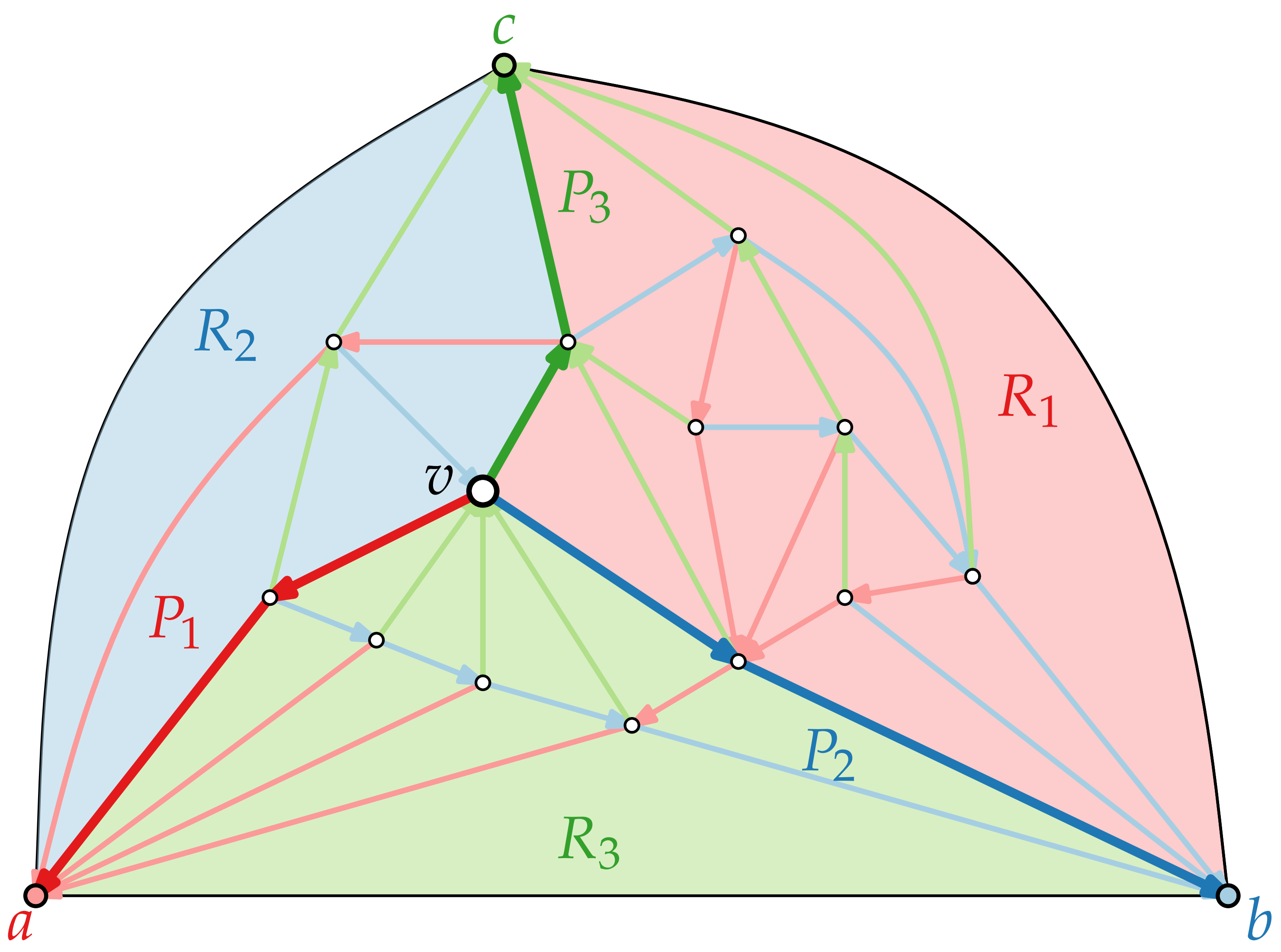

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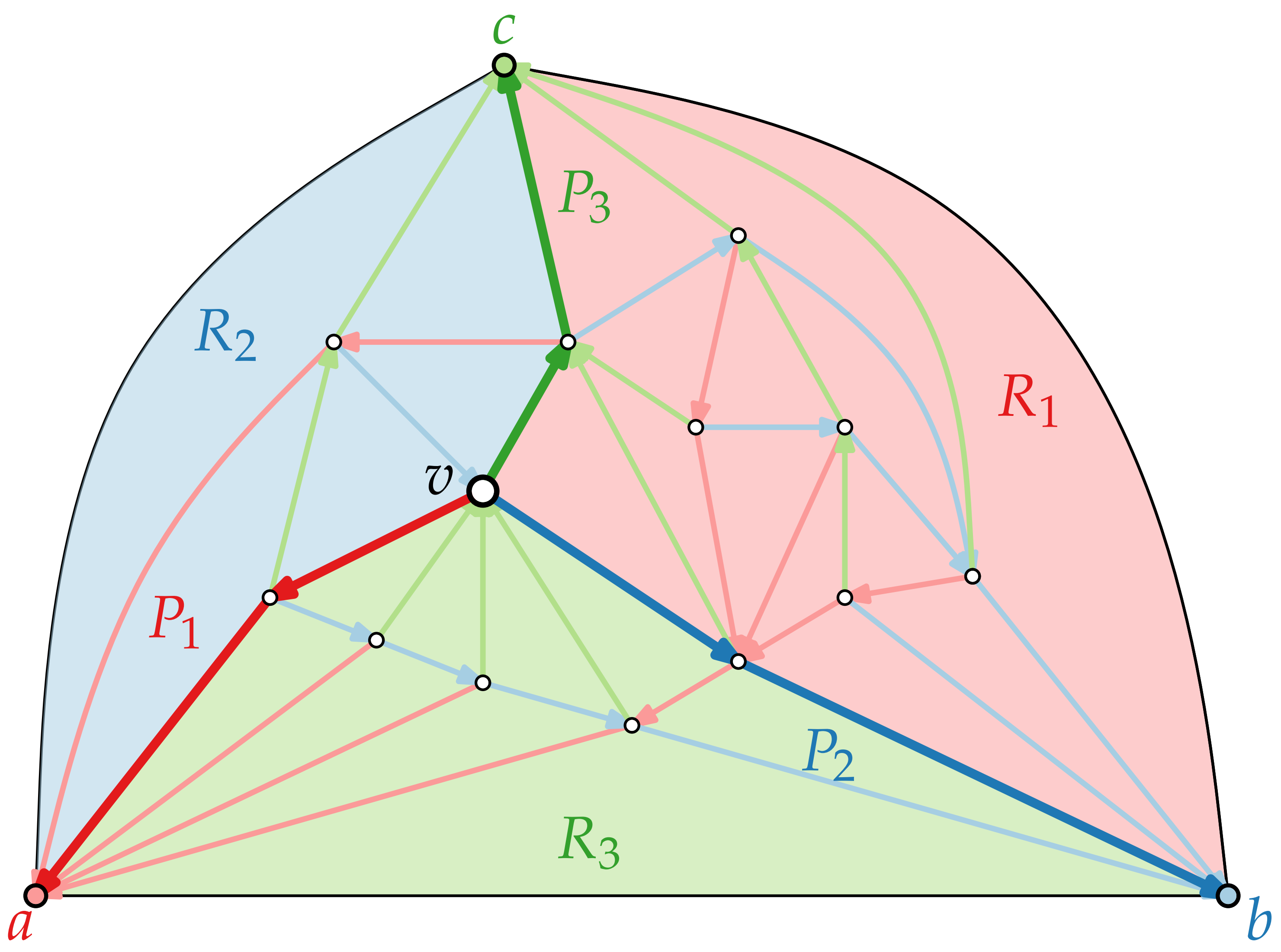

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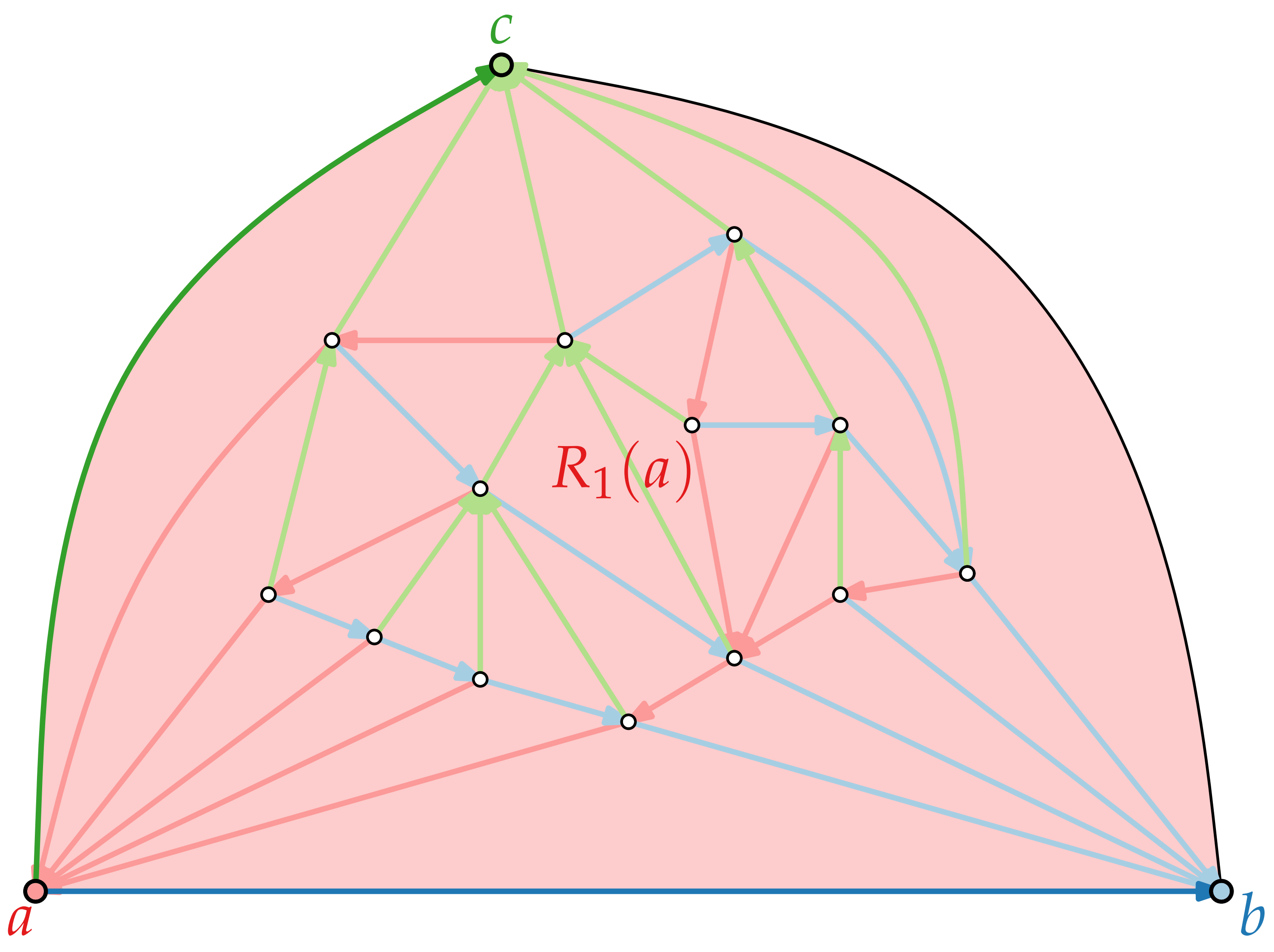

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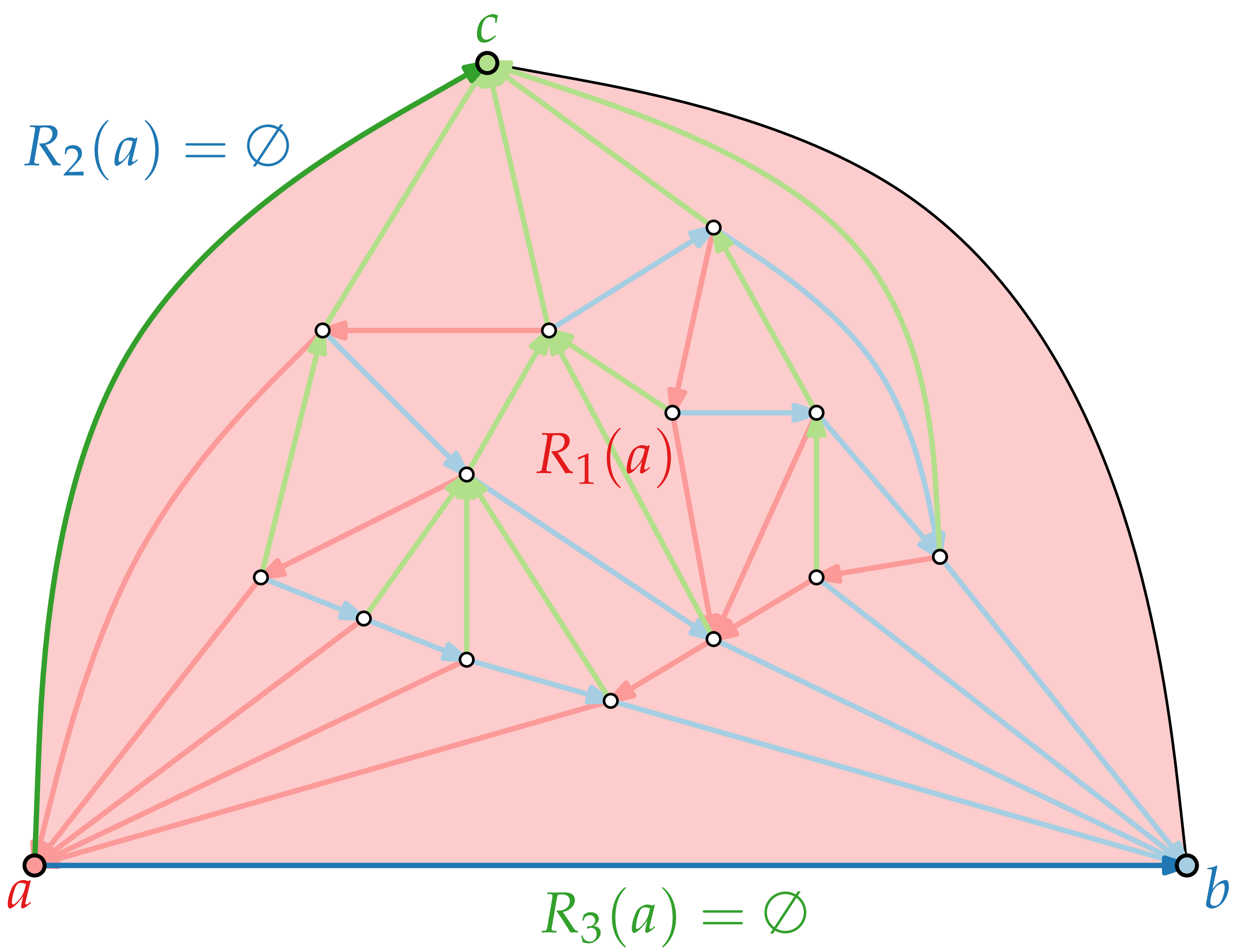

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Theorem. [Schnyder '89]
For a plane triangulation G, the mapping

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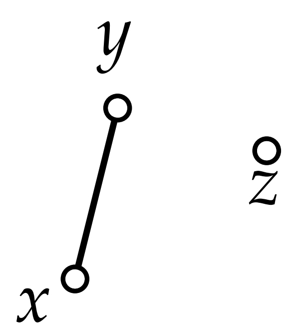

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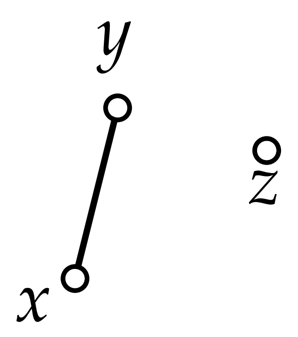

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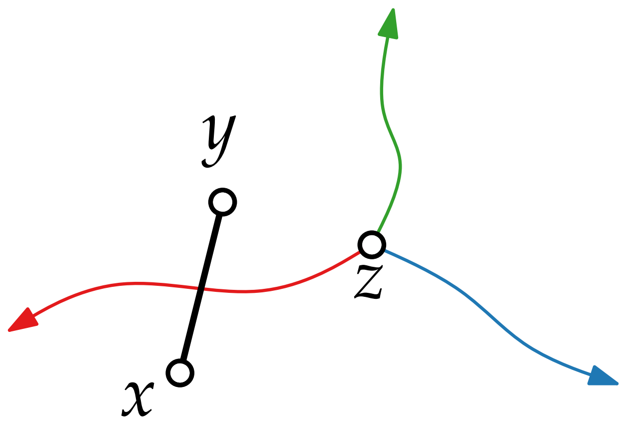

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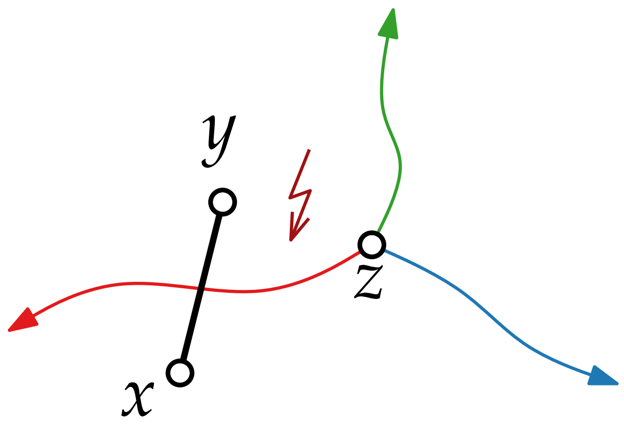

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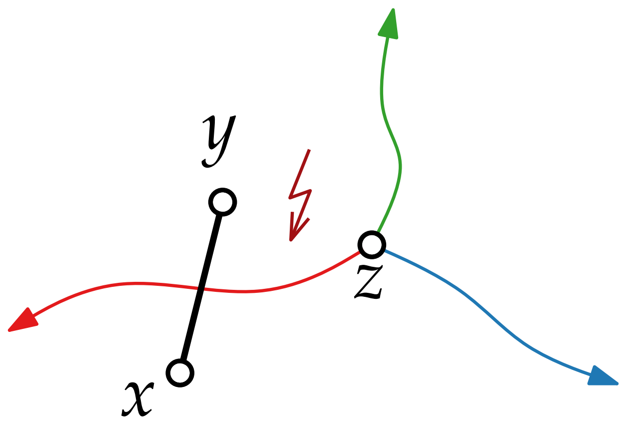

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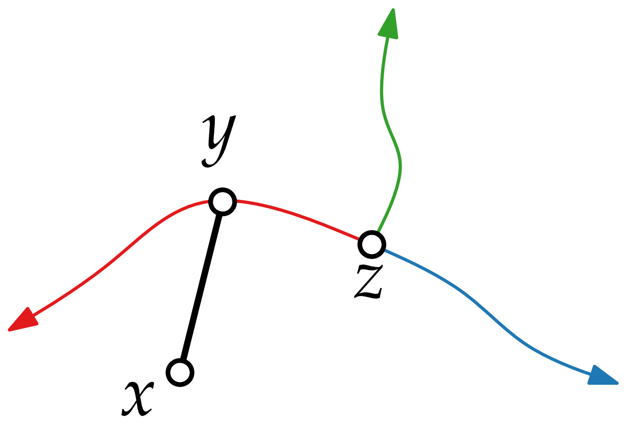

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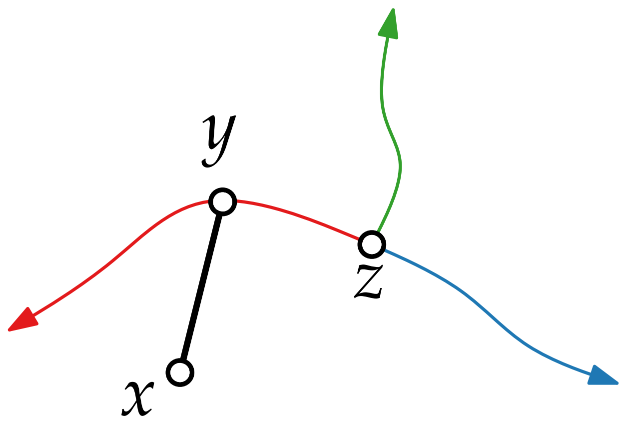

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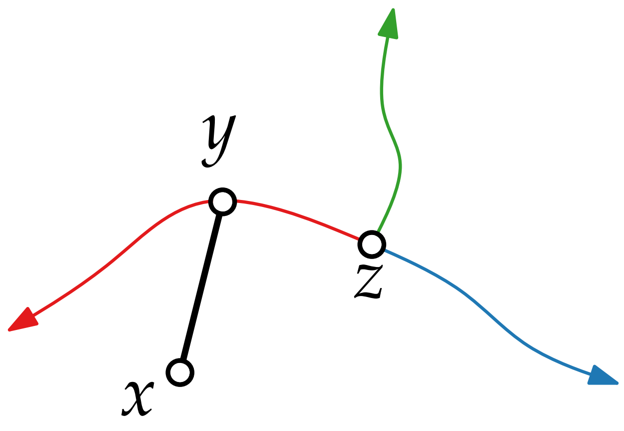

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is a barycentric representation of G, which thus gives a planar straight-line drawing of G on the $(2n-5) \times (2n-5)$ grid.

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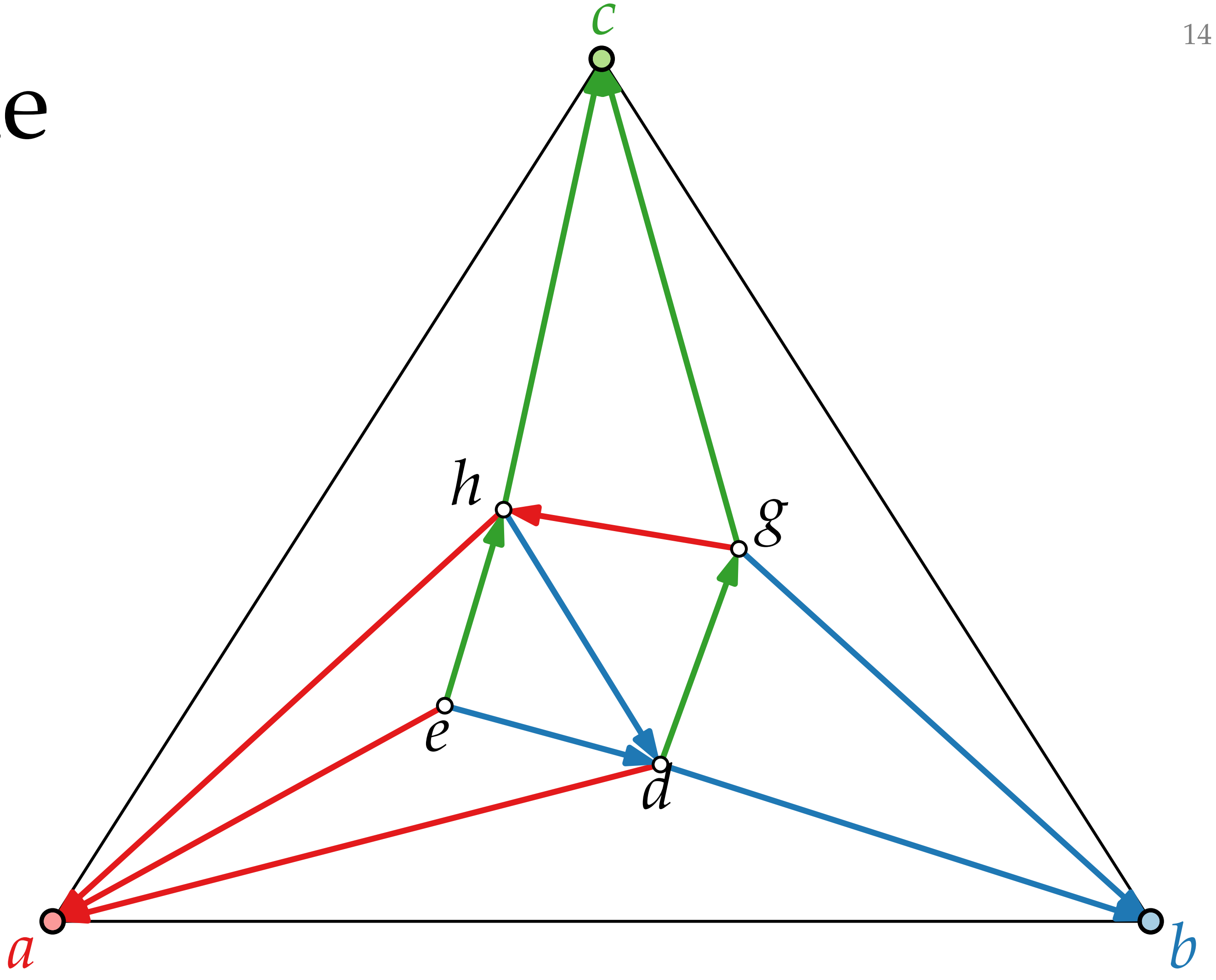

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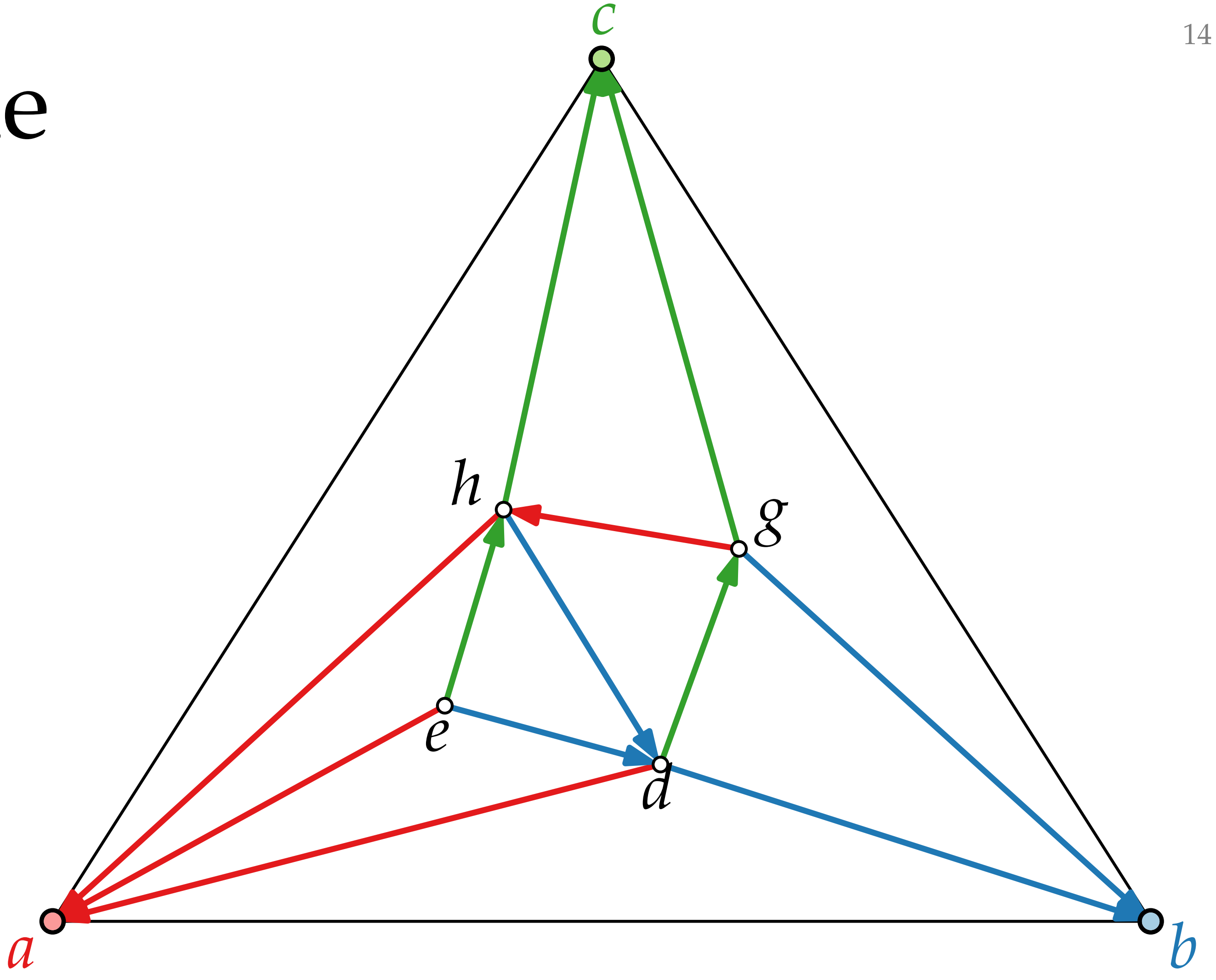

$n = 7,\ 2n - 5 = 9$

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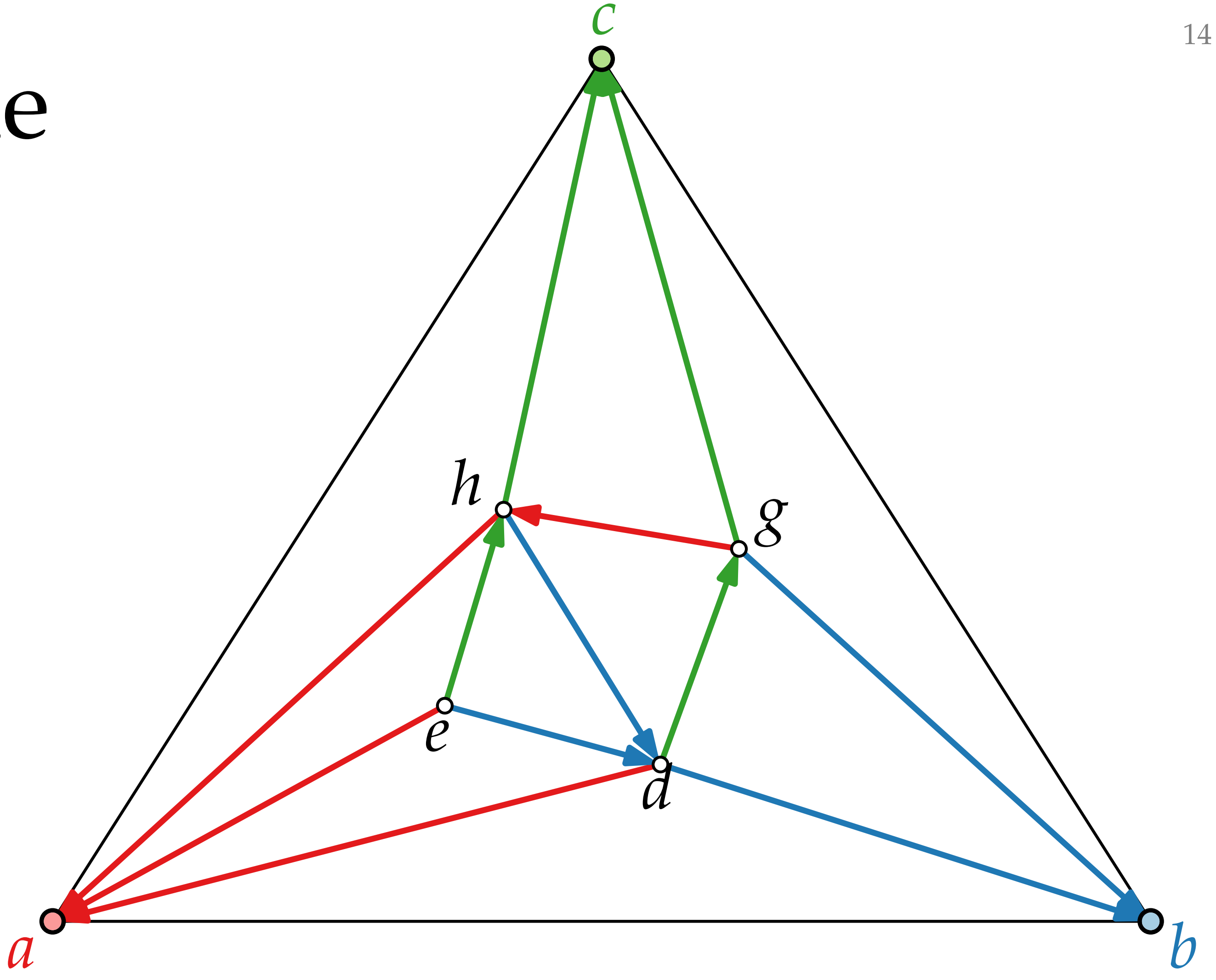

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$f(a) = (9, 0, 0)$

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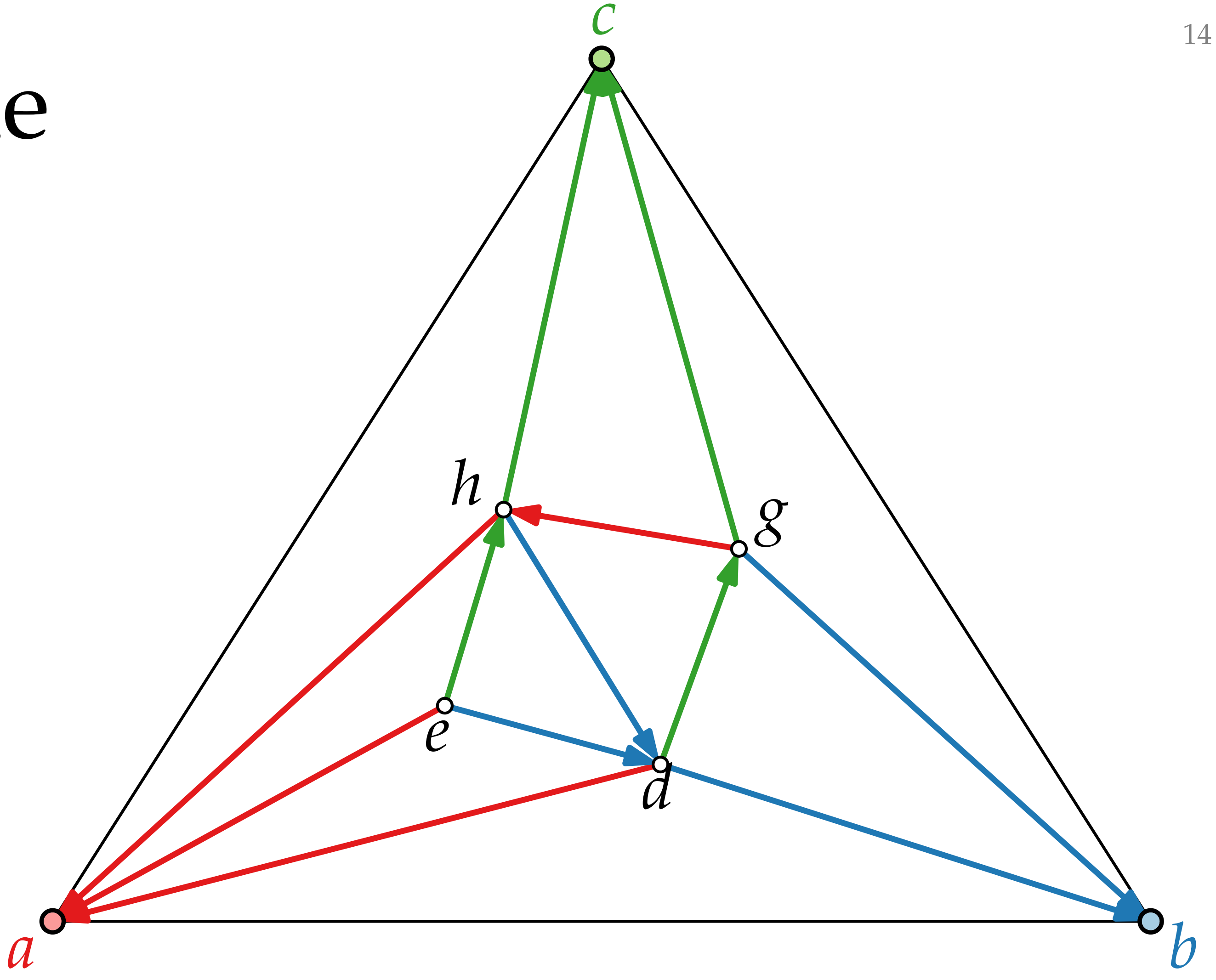

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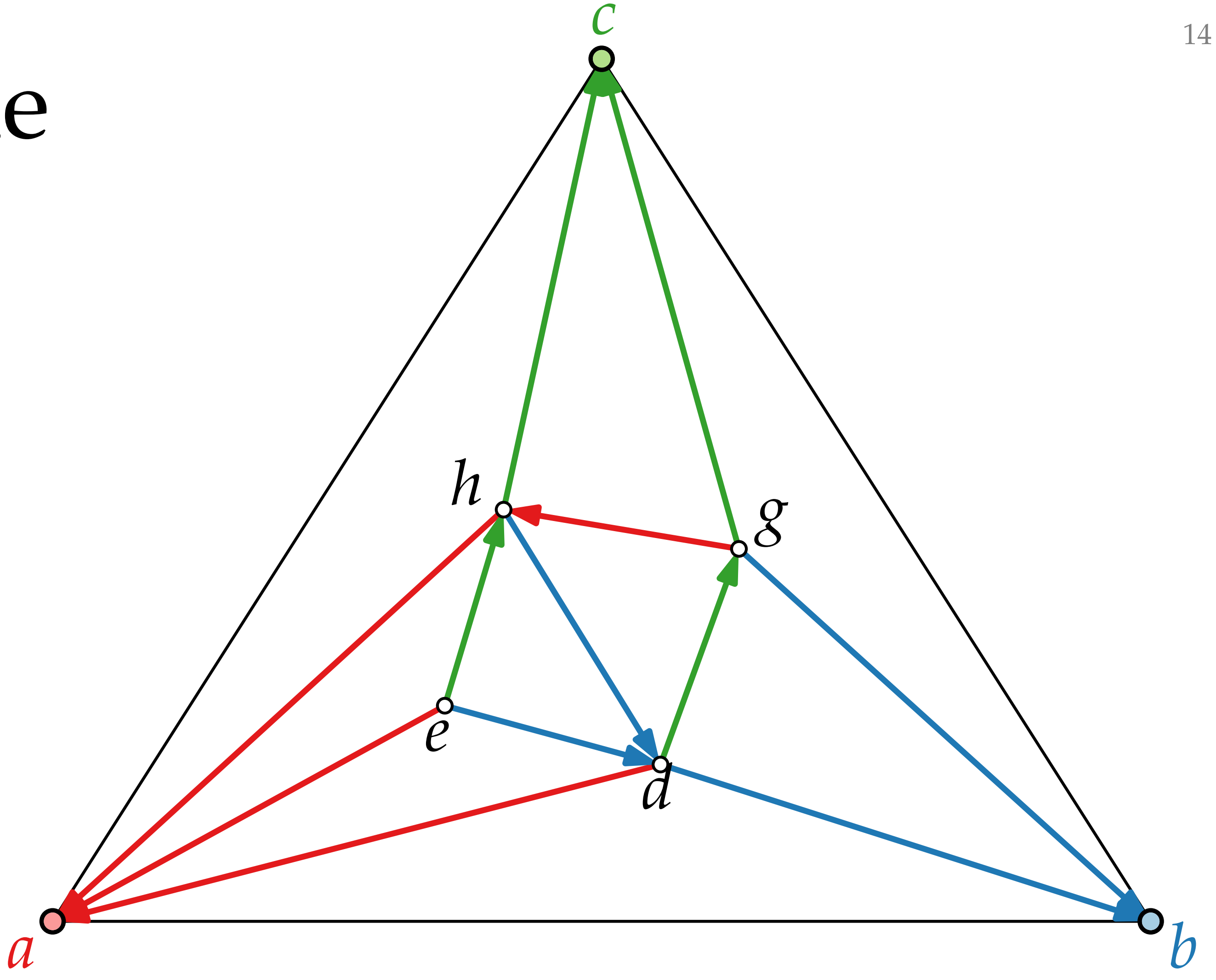

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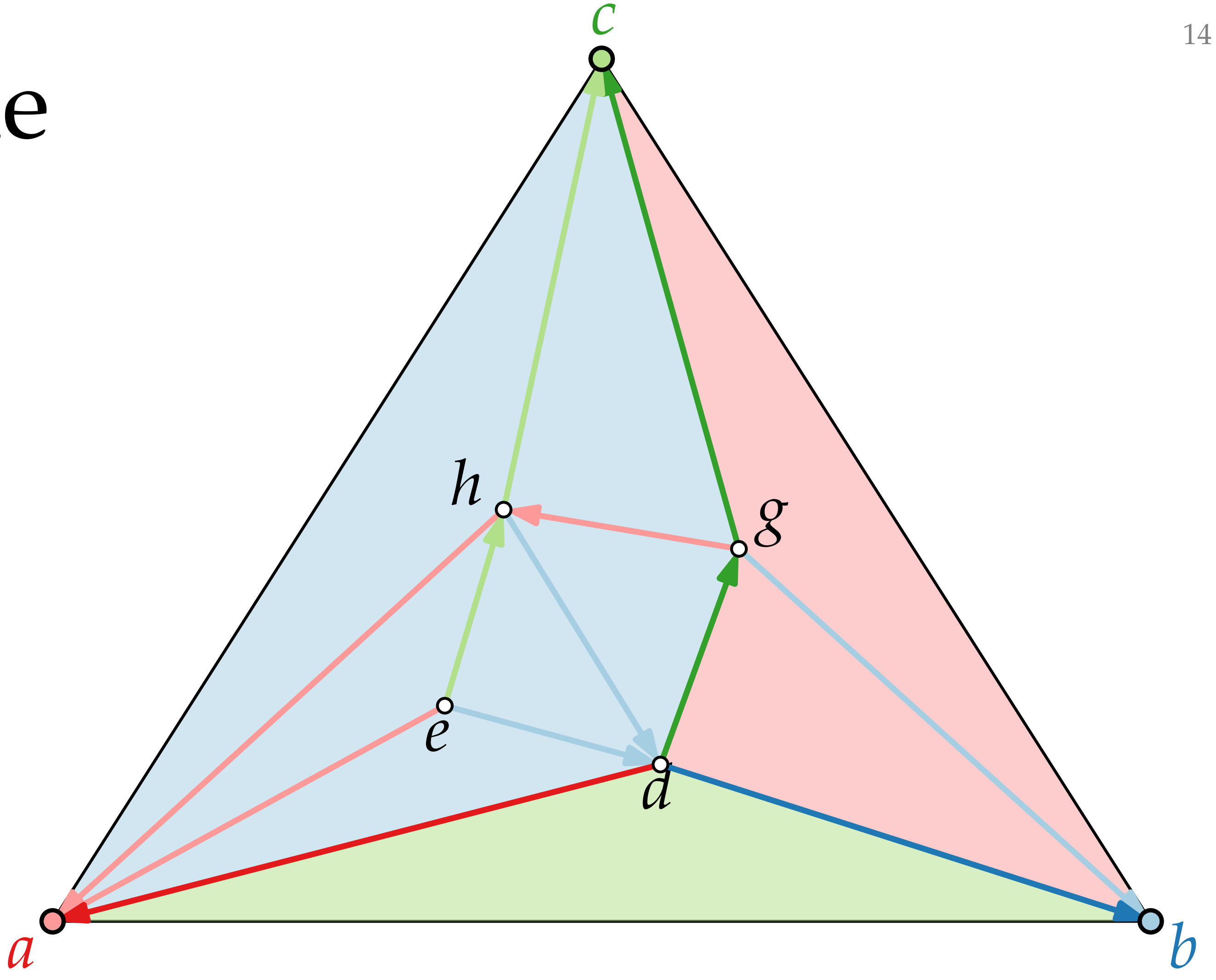

$n = 7, 2n - 5 = 9$ $\quad f(d) = (2, 6, 1)$

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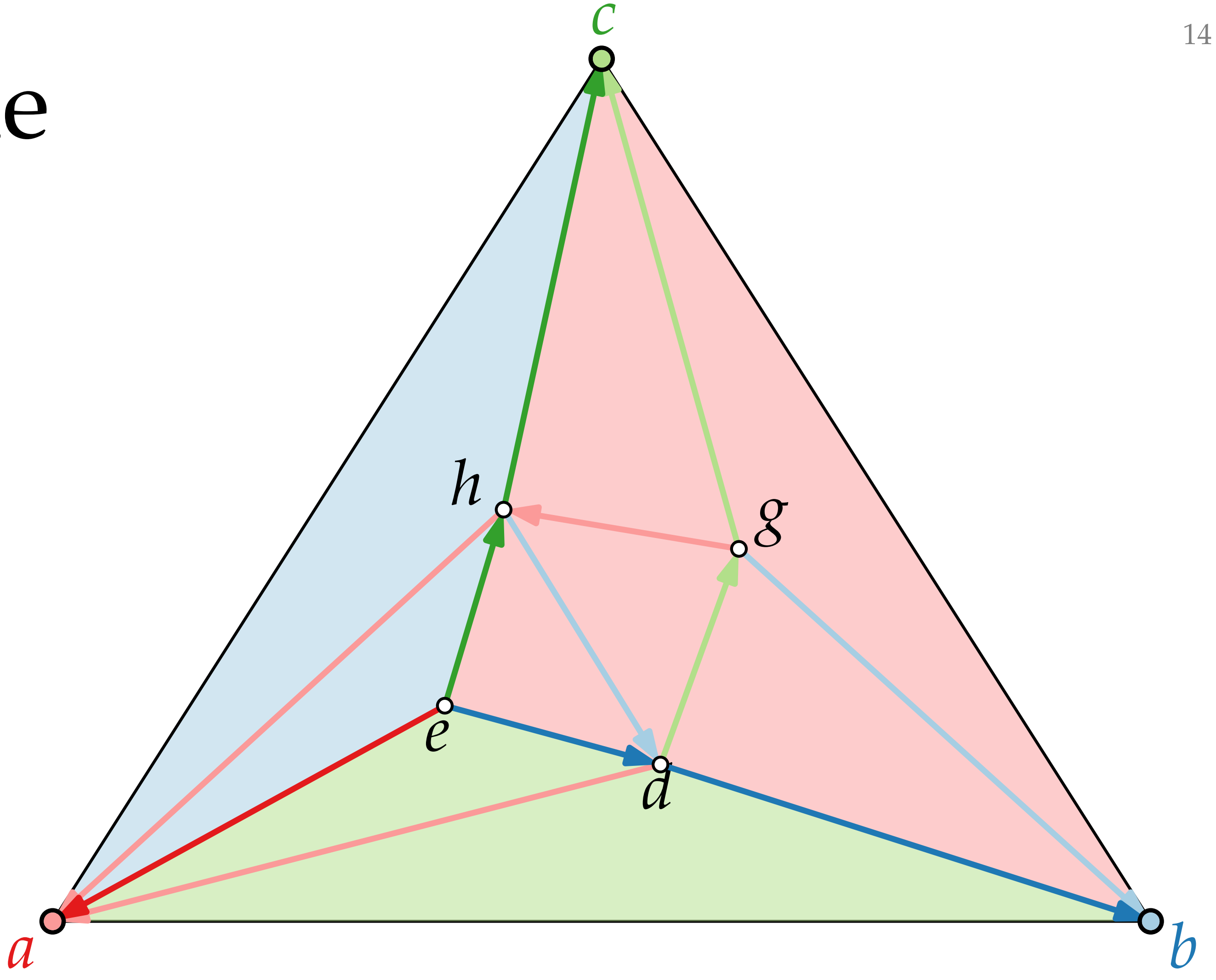

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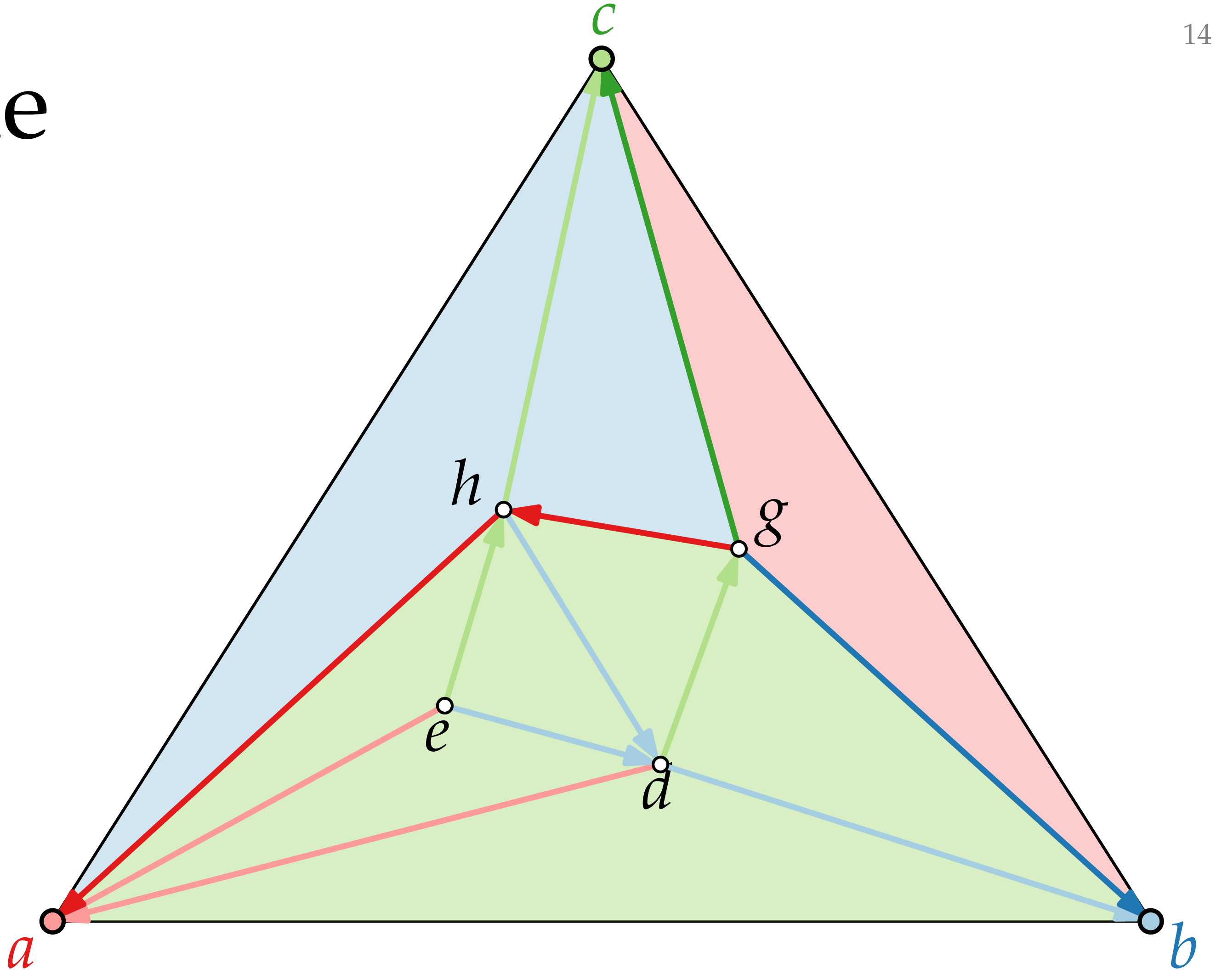

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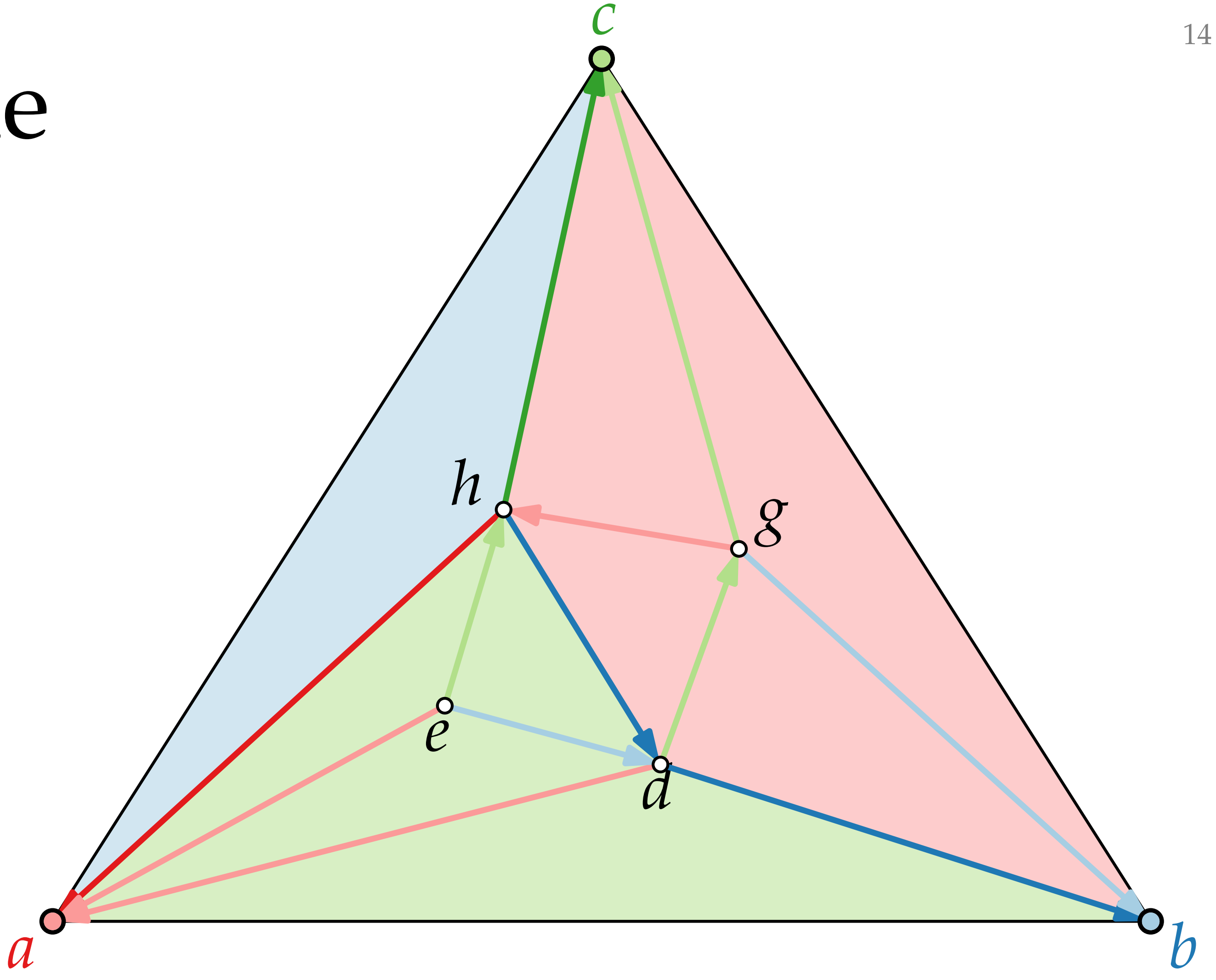

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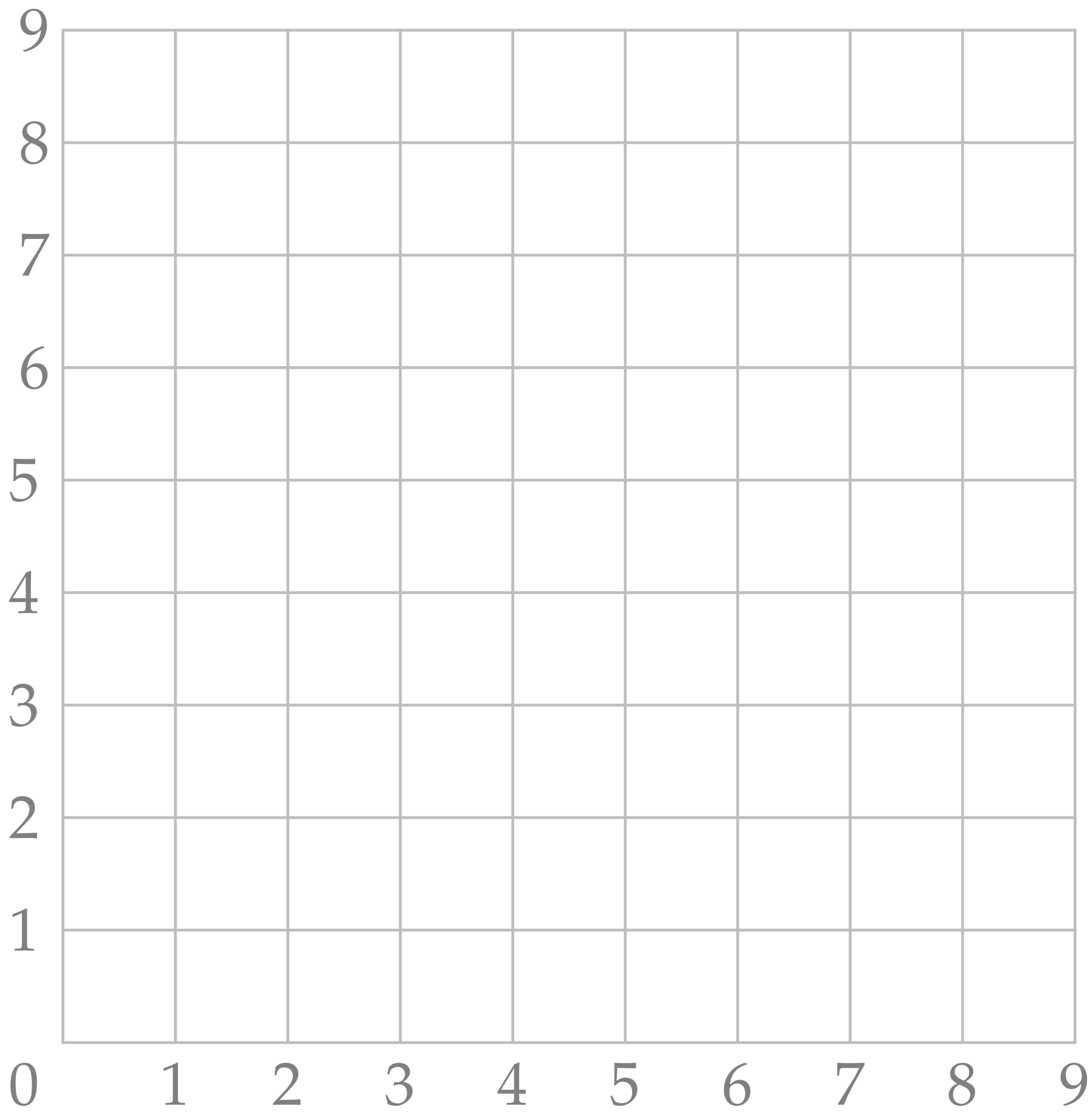
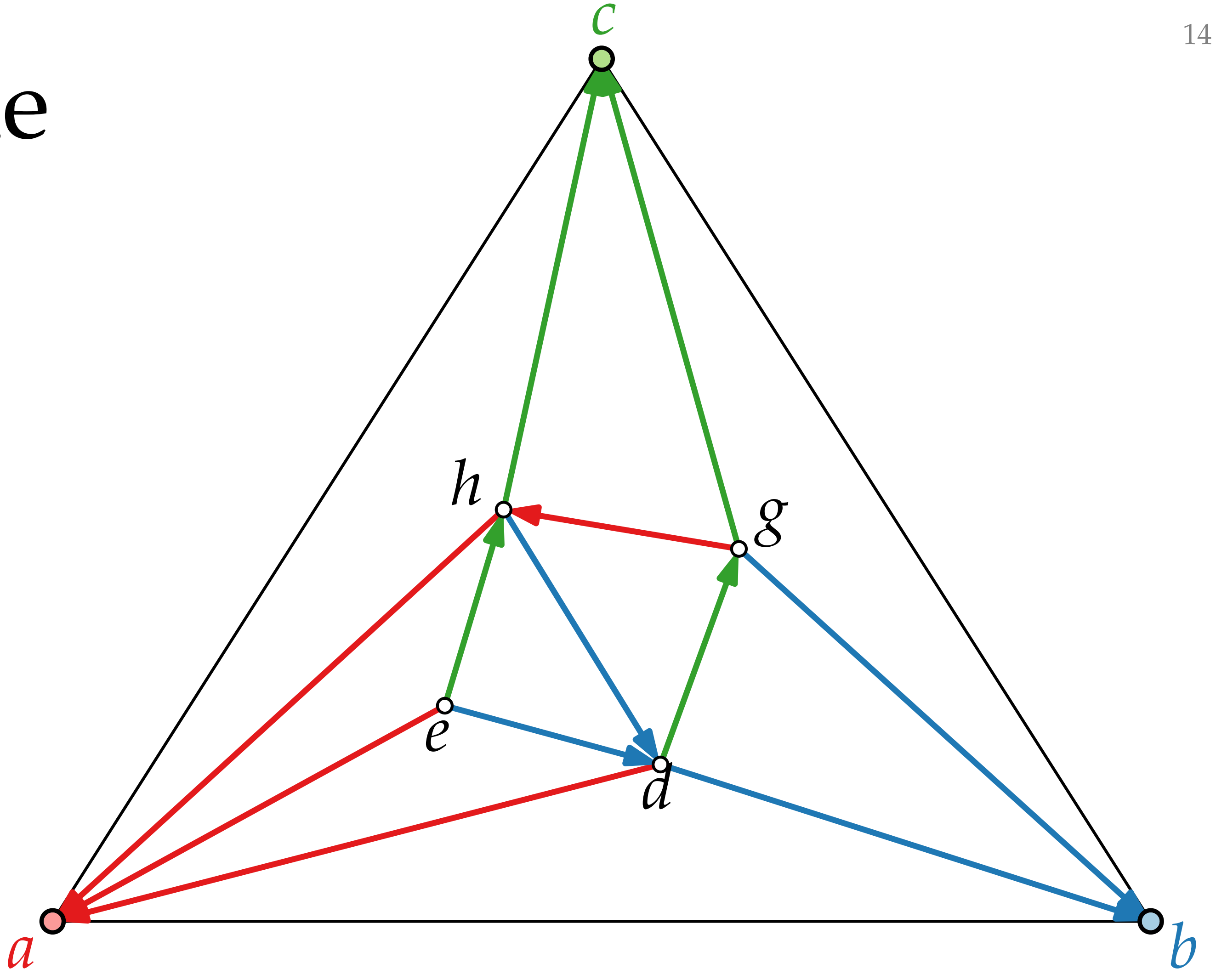
$f(h) = (4, 1, 4)$

Schnyder Drawing – Example





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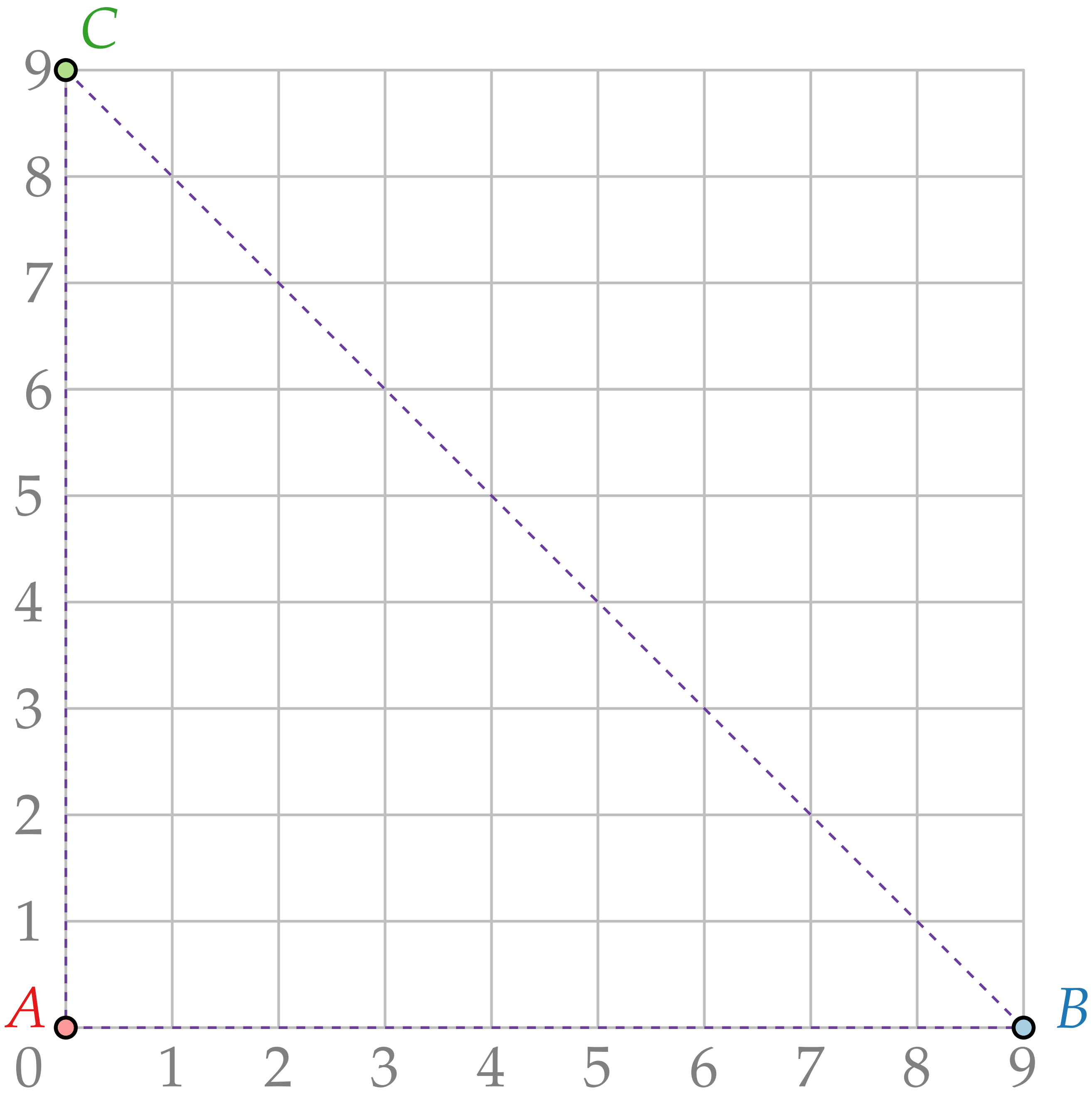

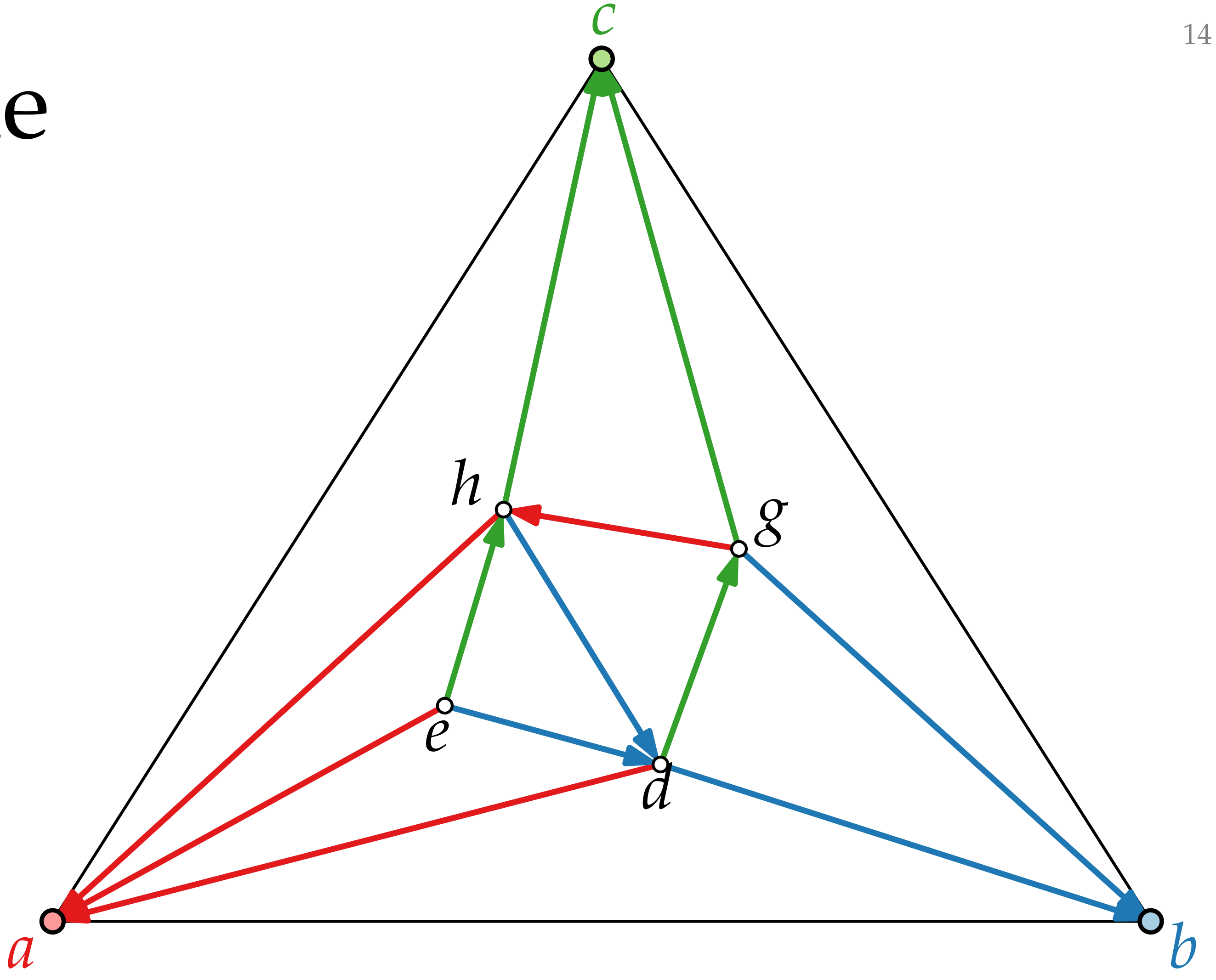

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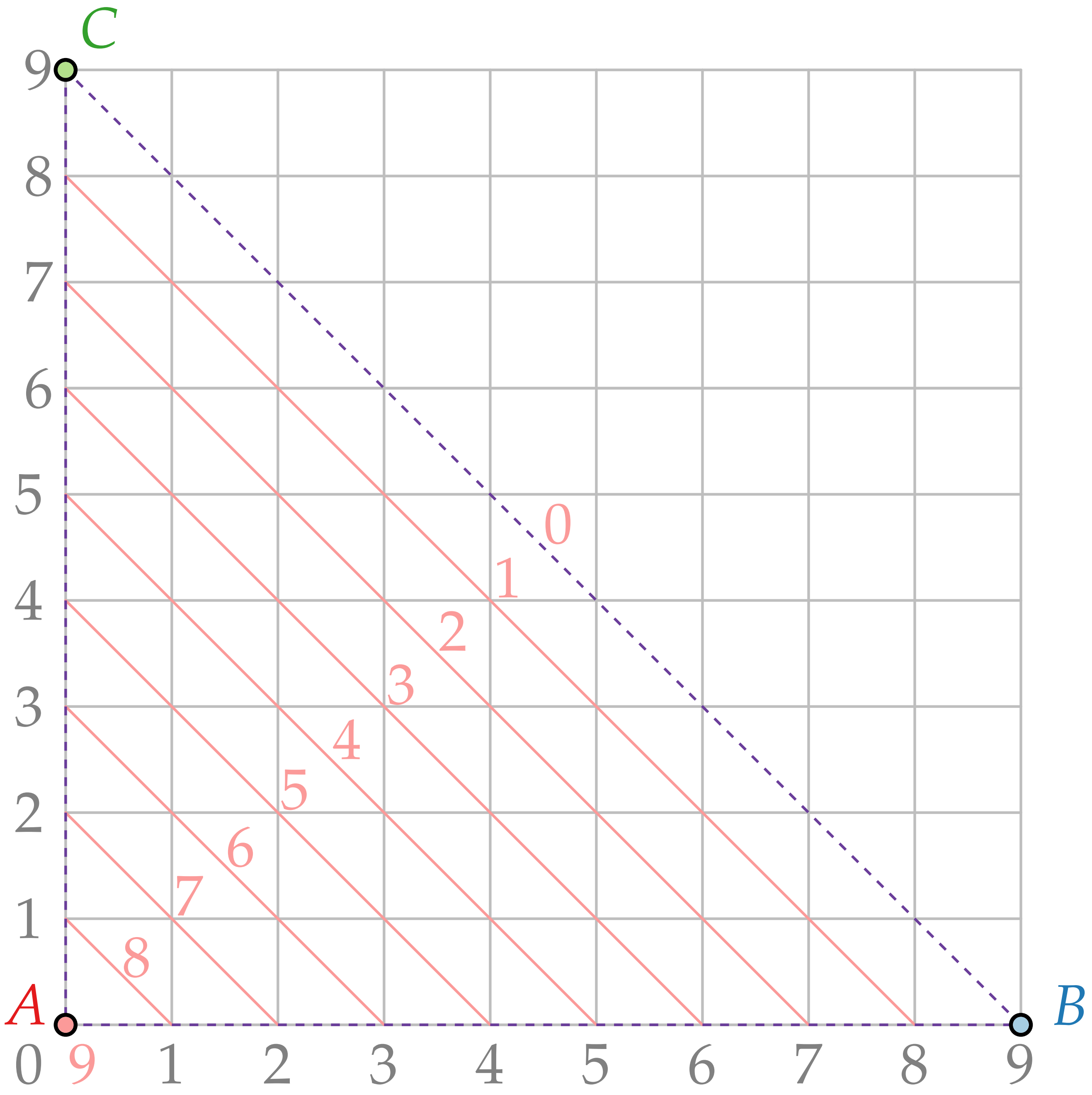

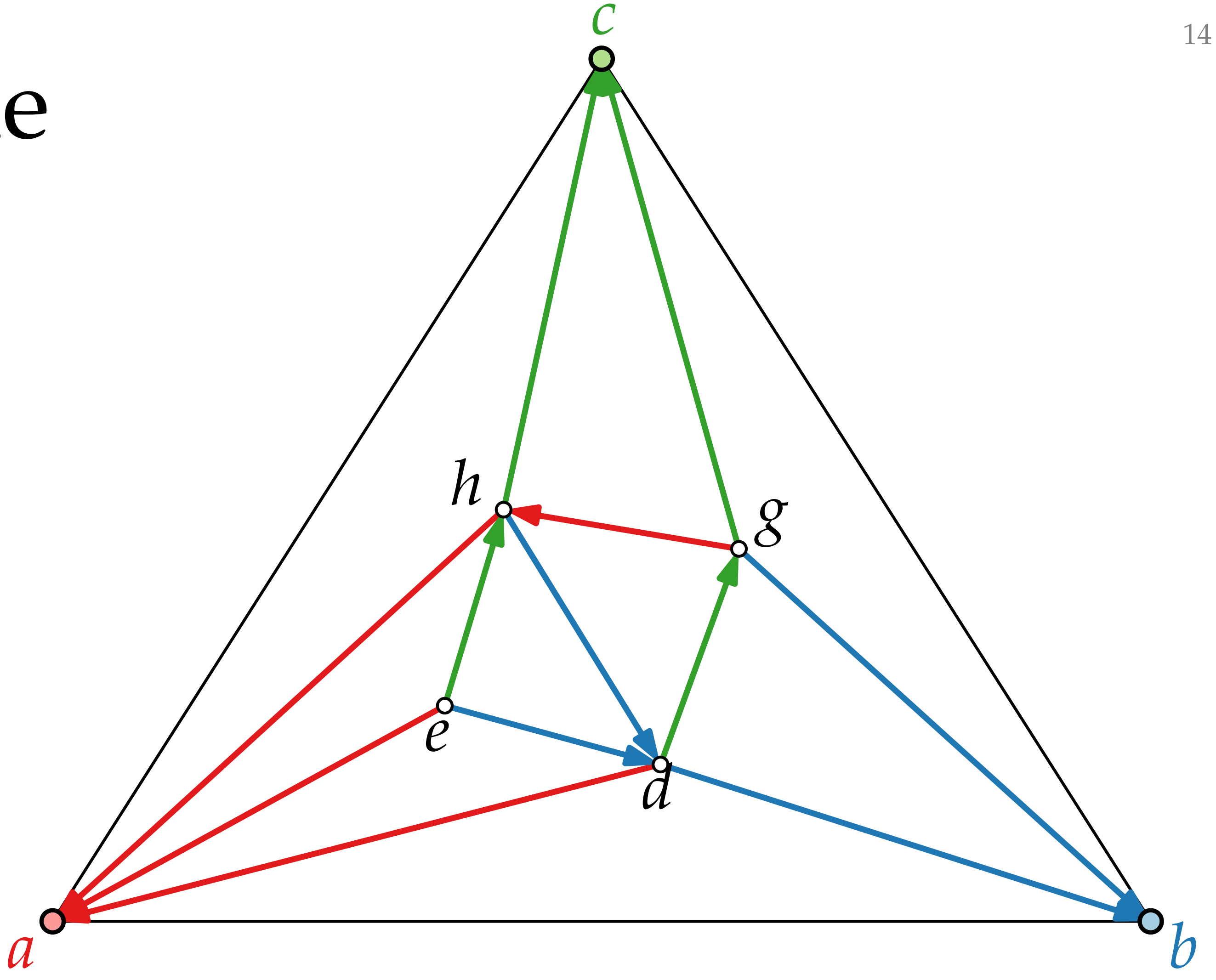

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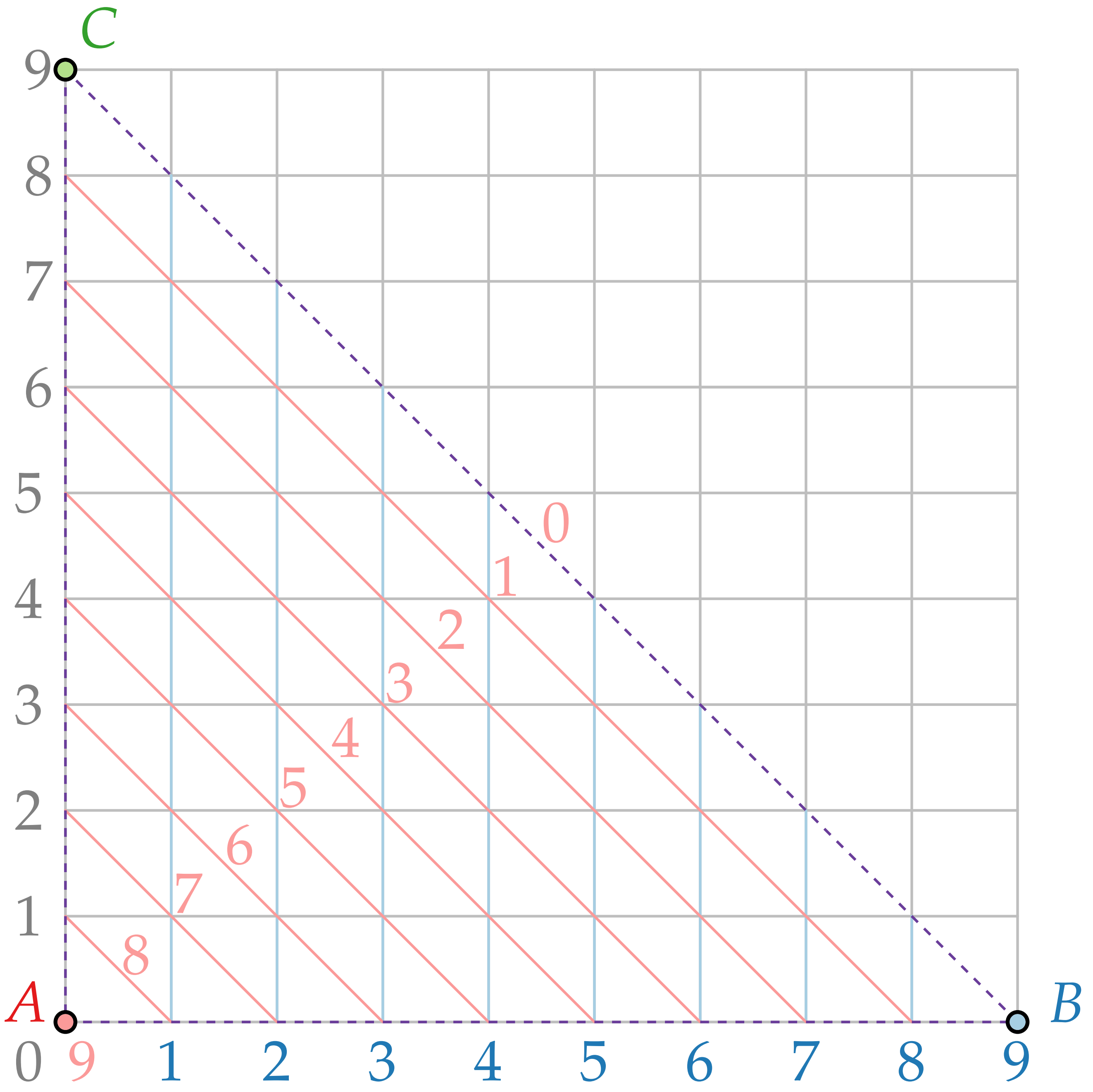

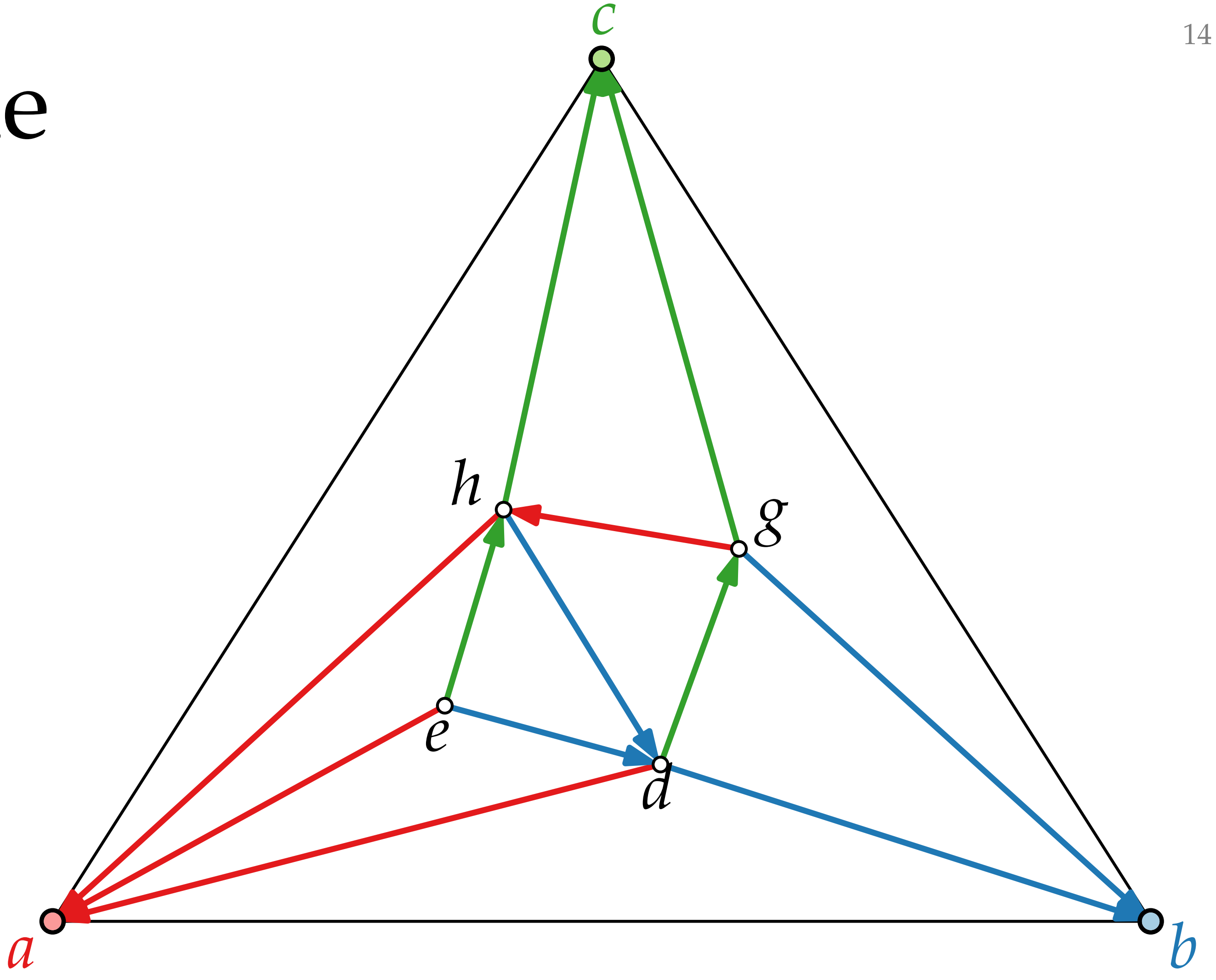

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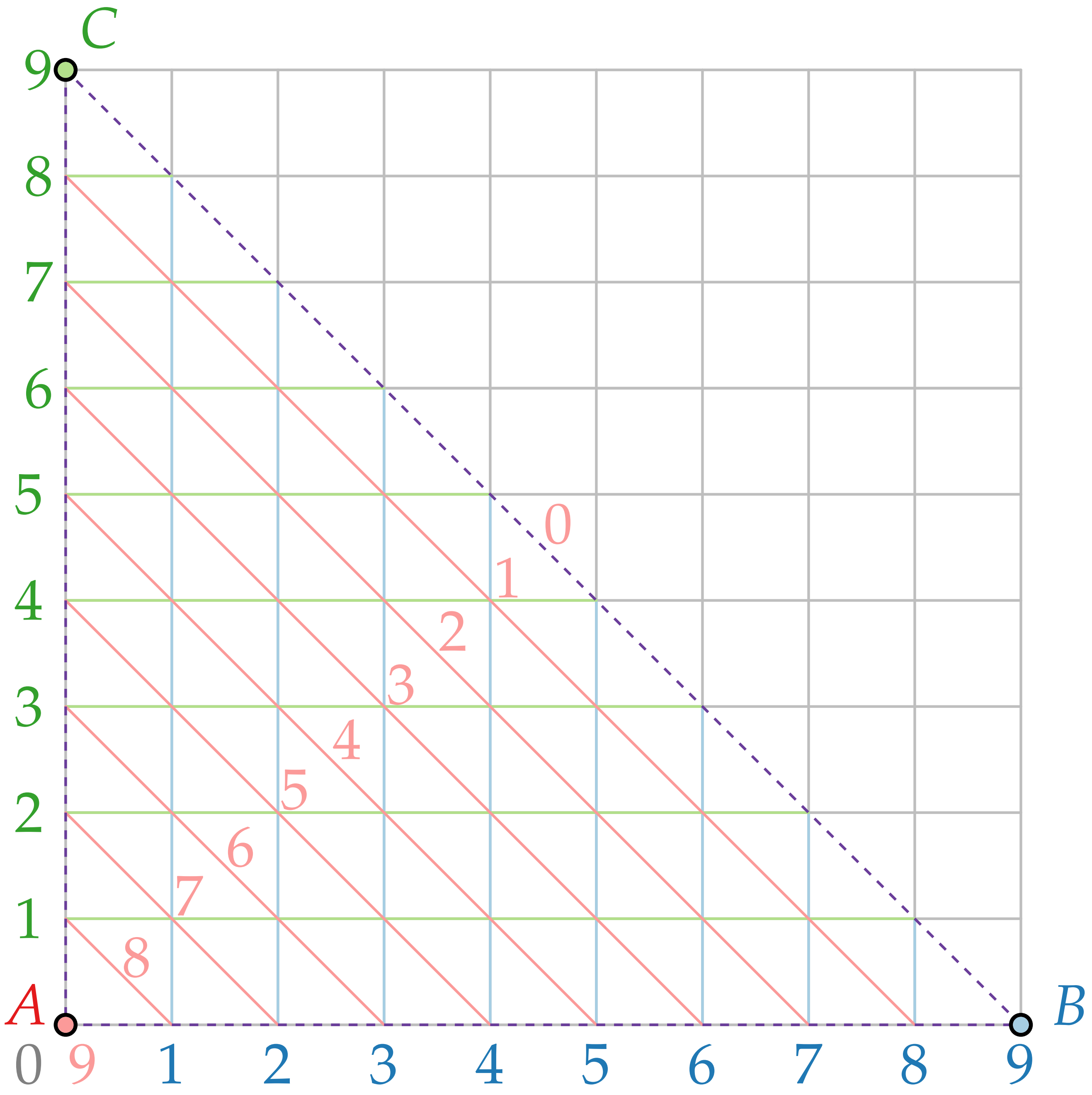

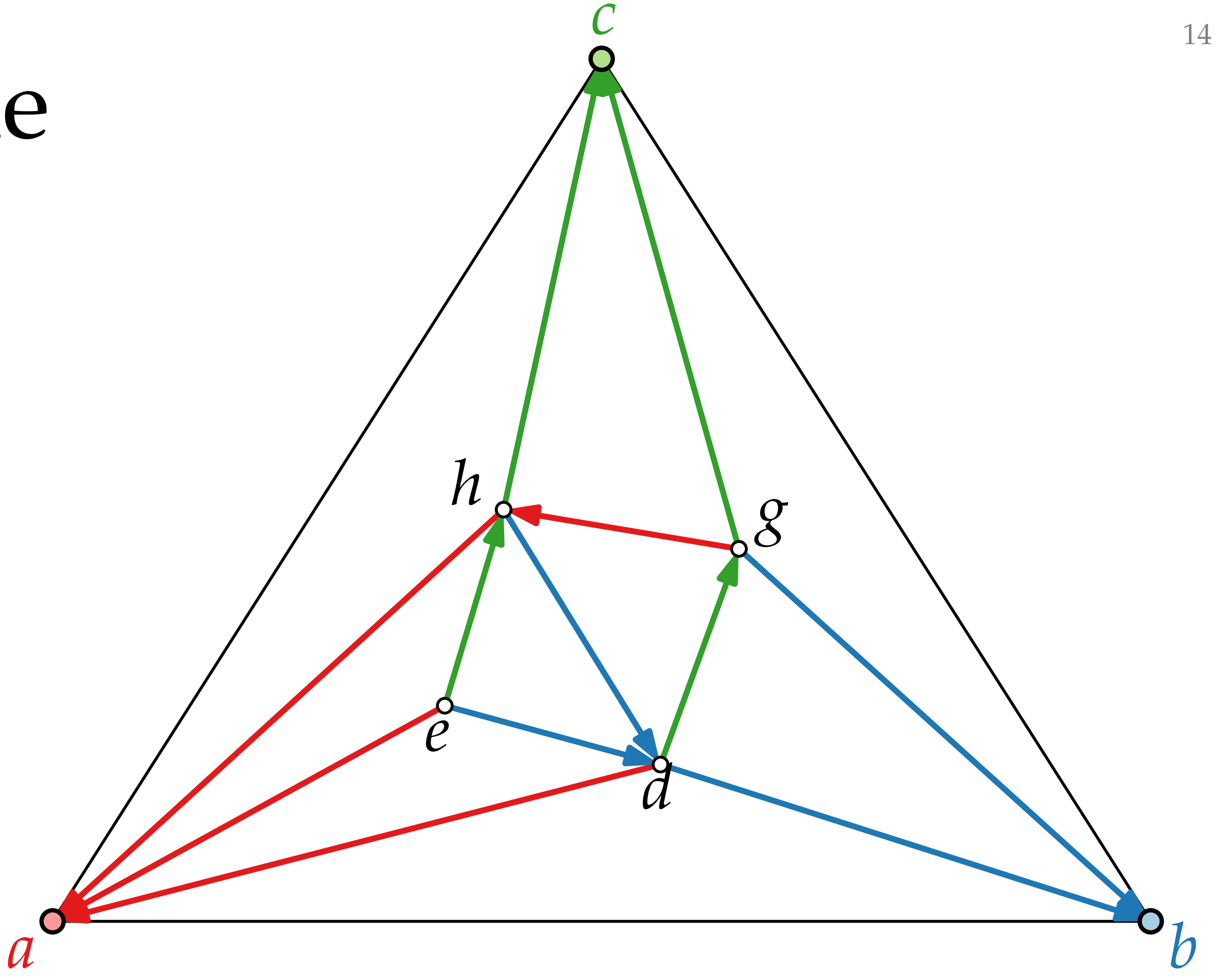

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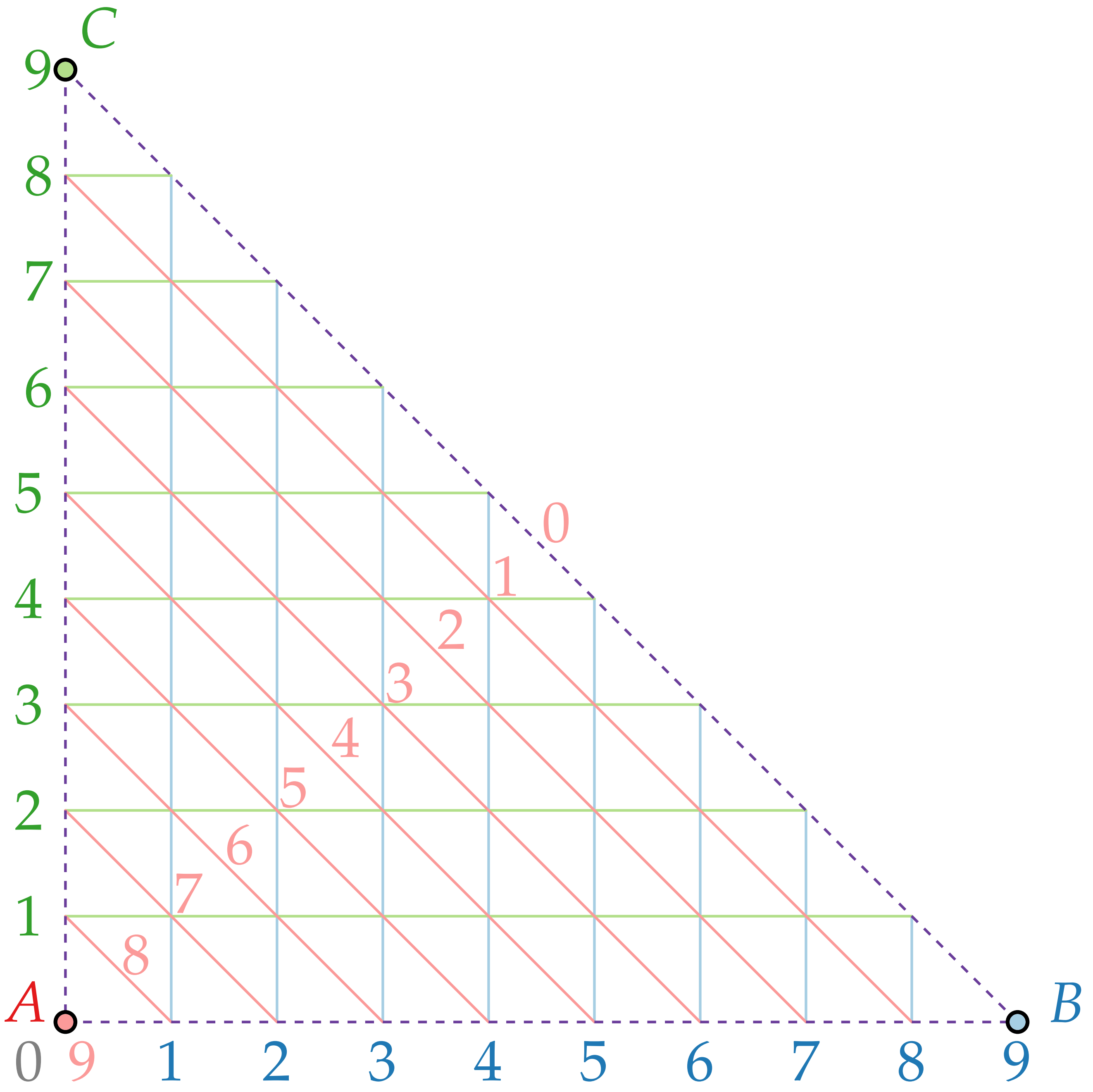

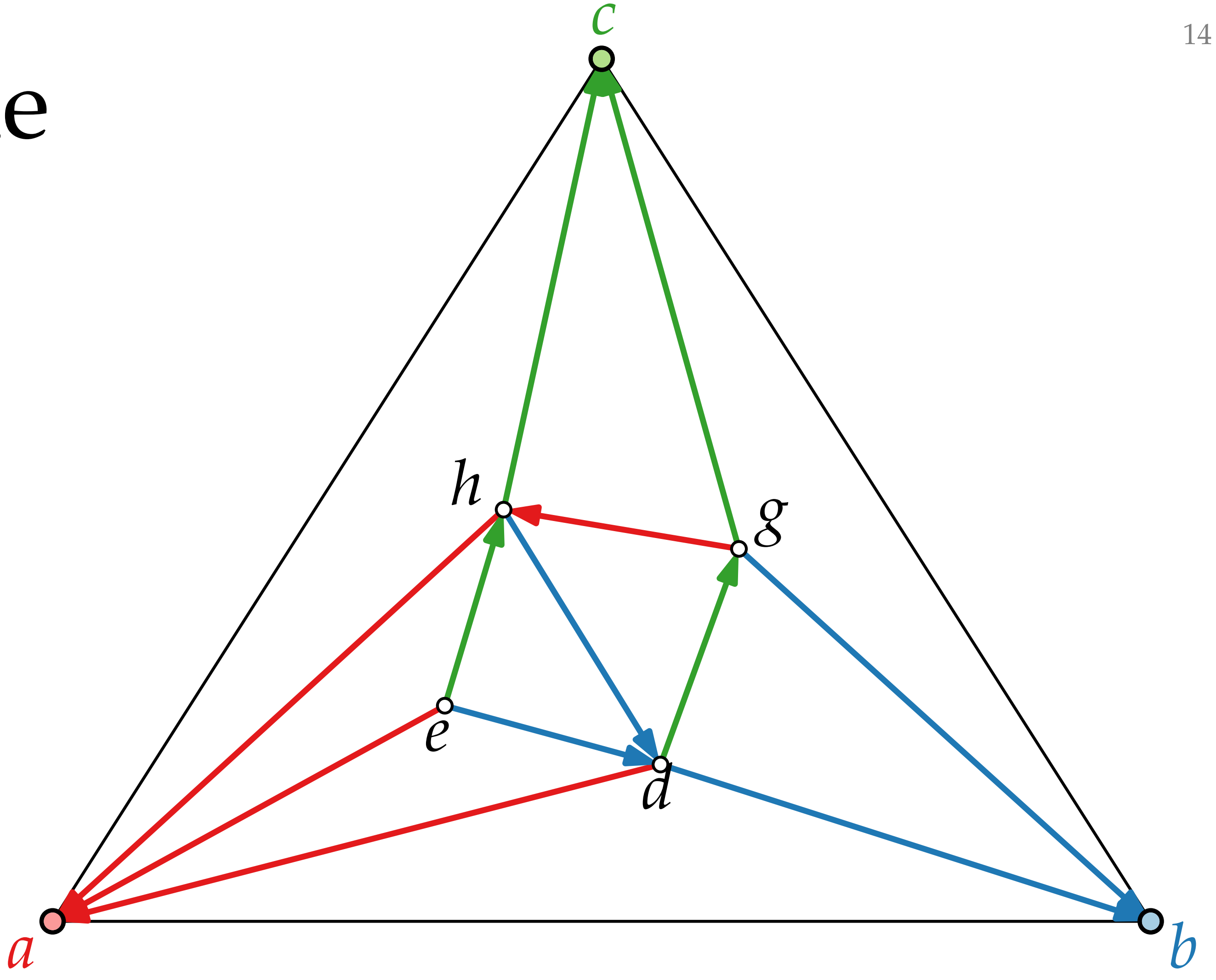

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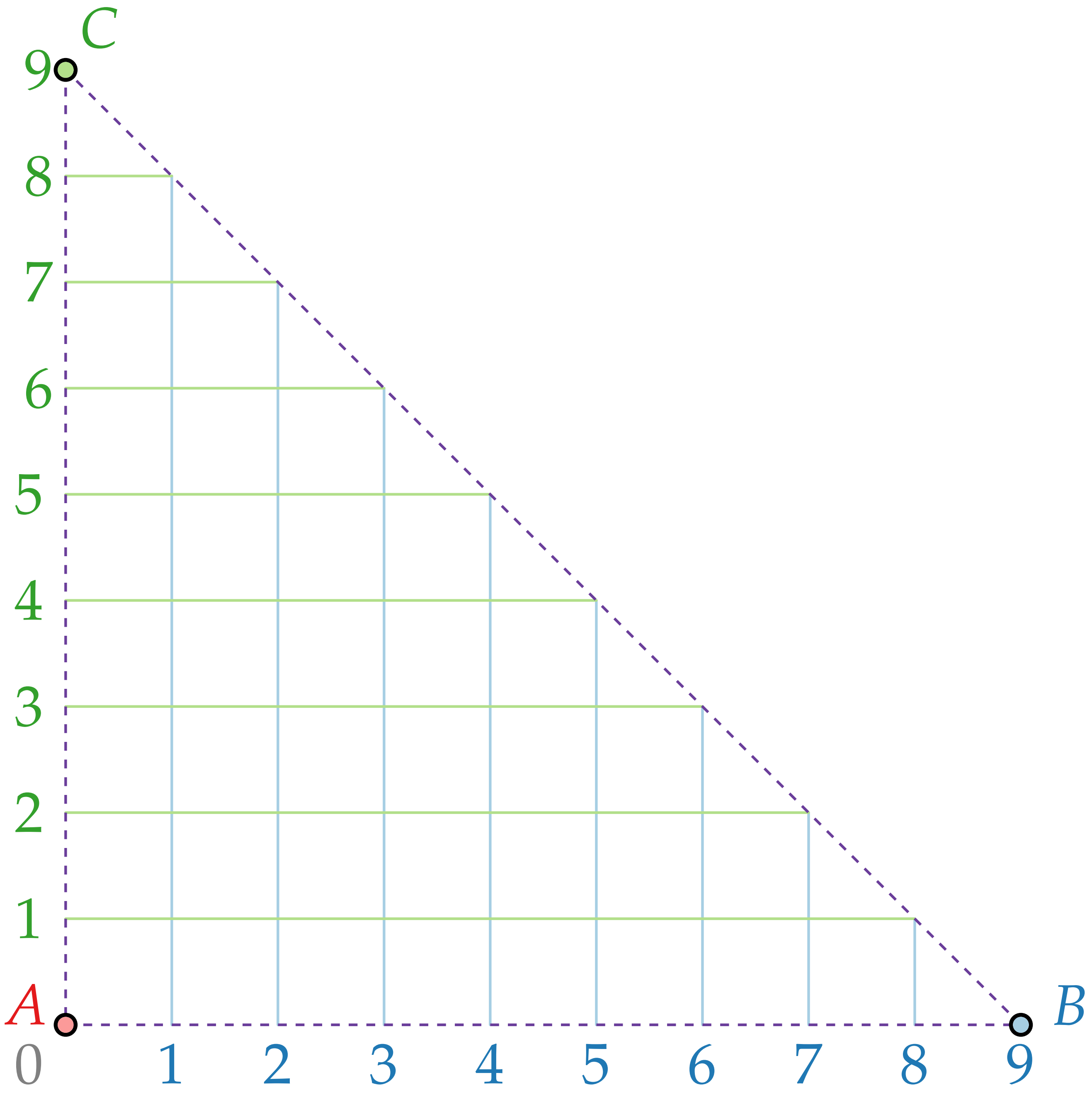

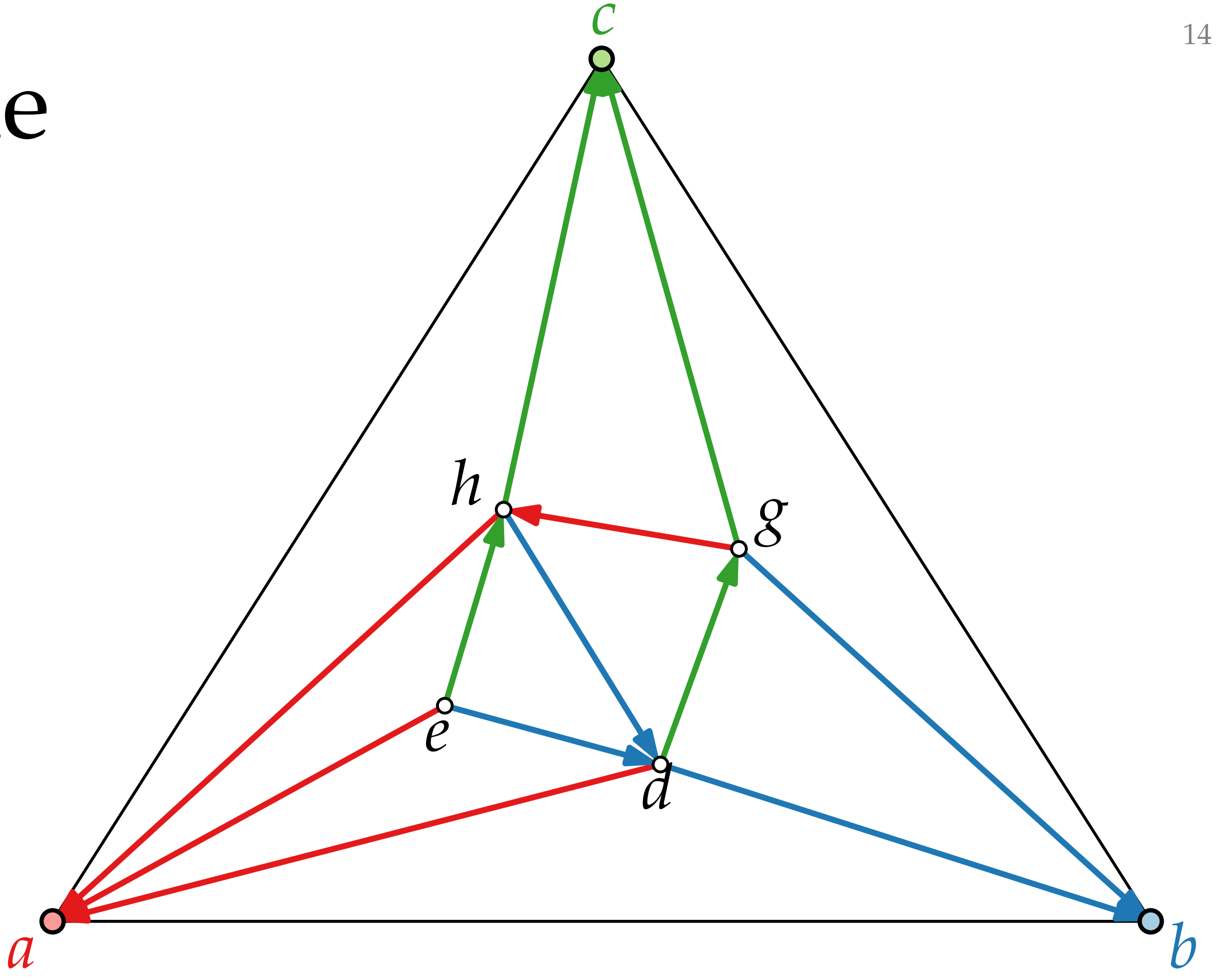

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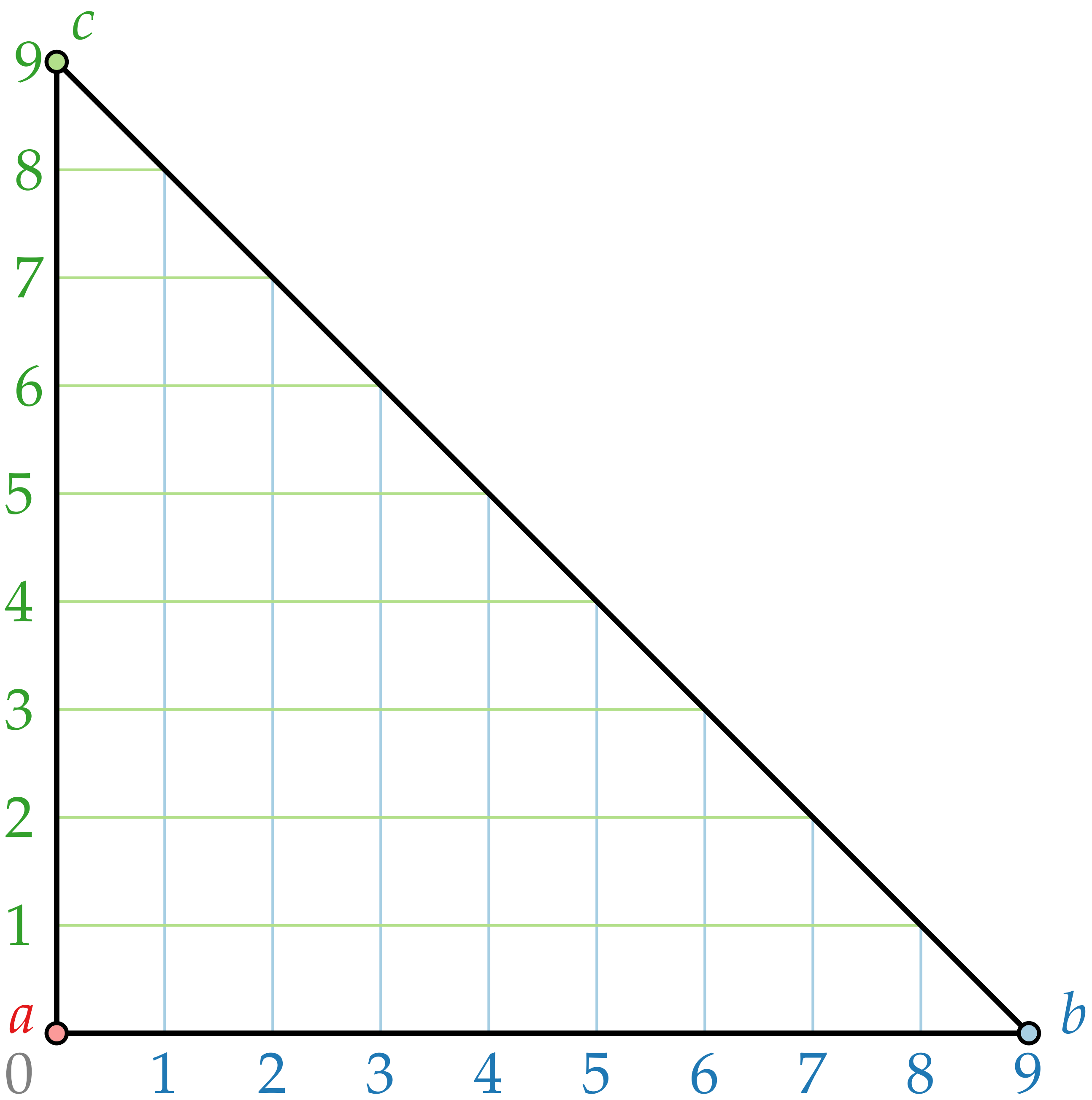

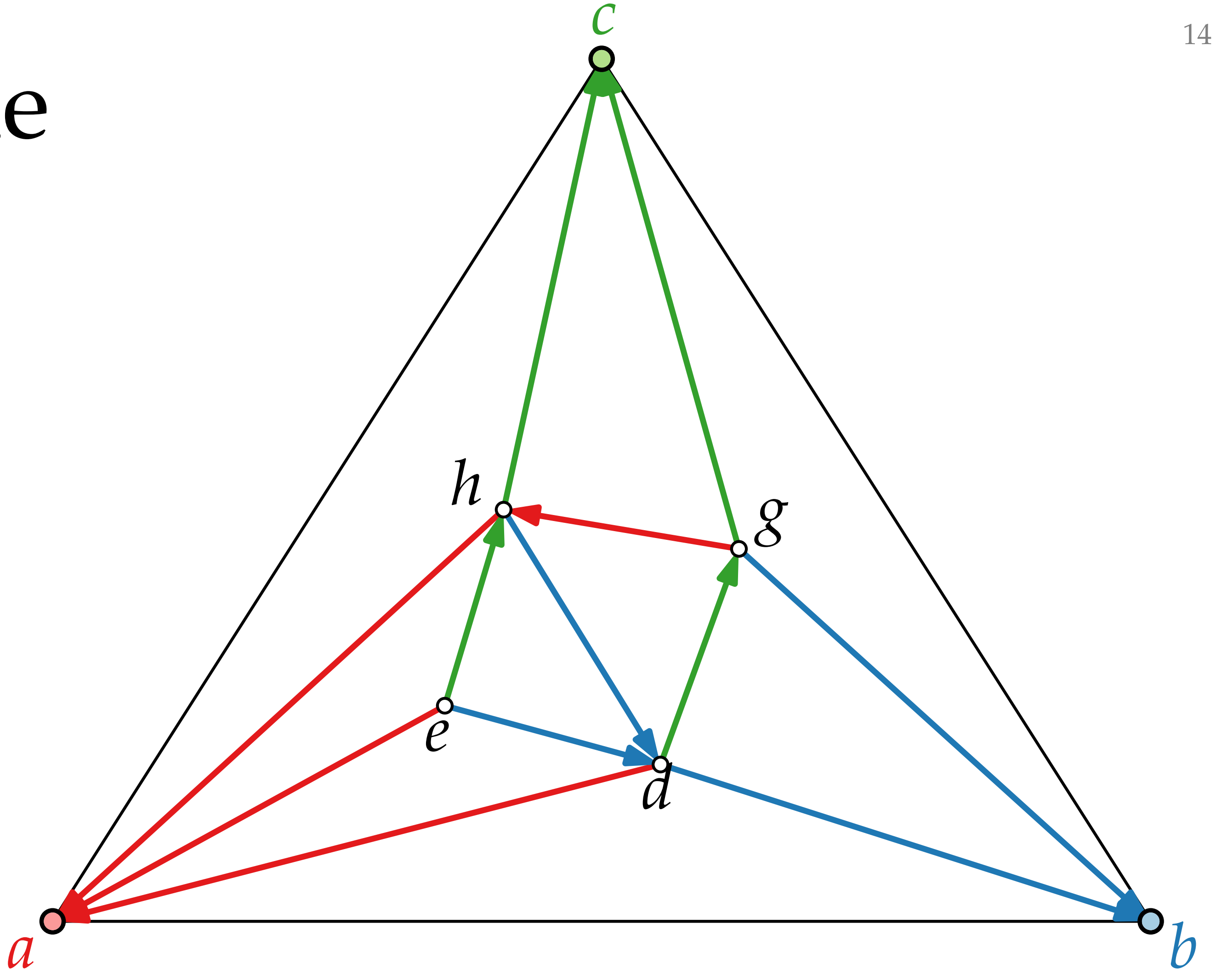

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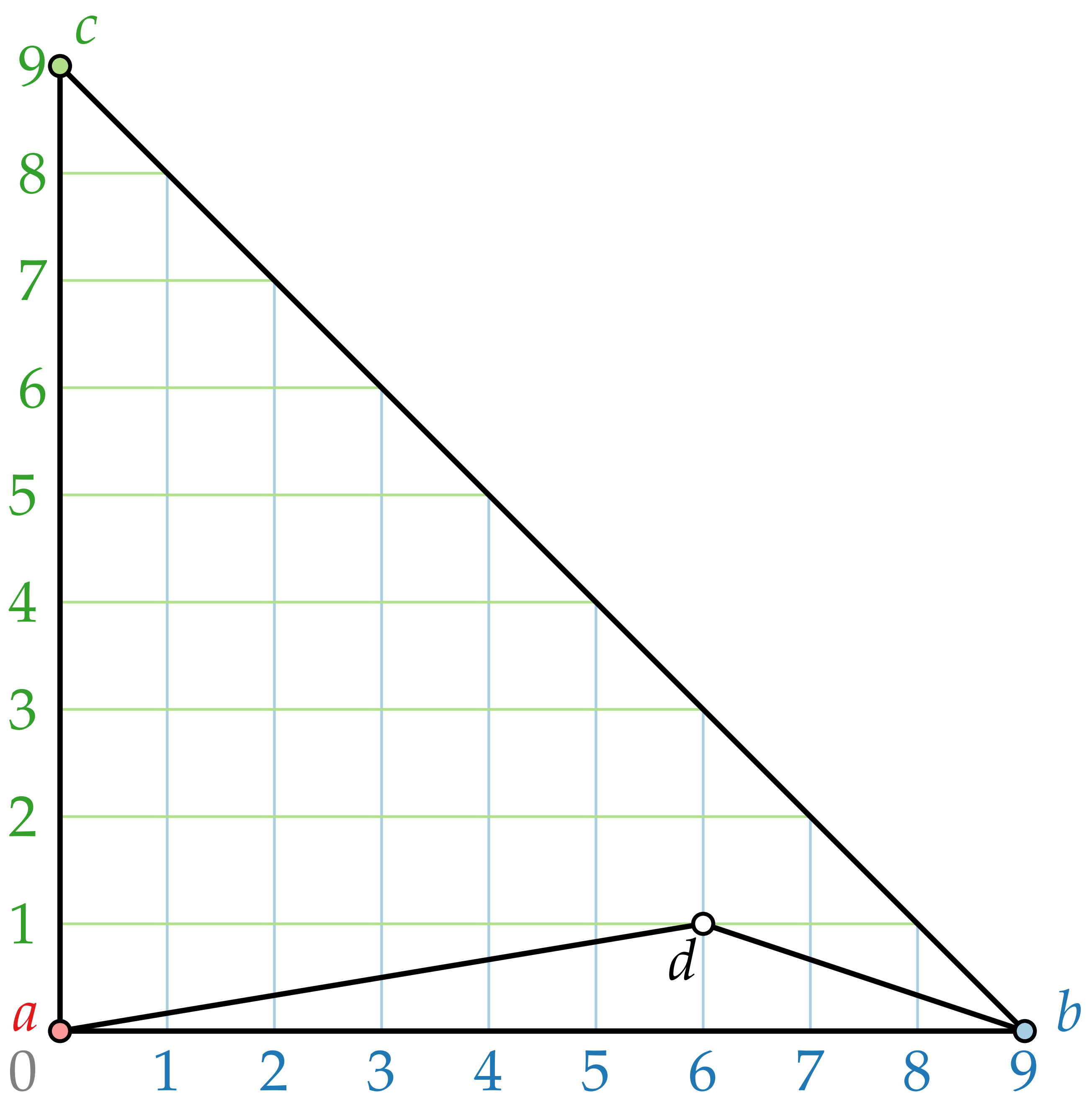

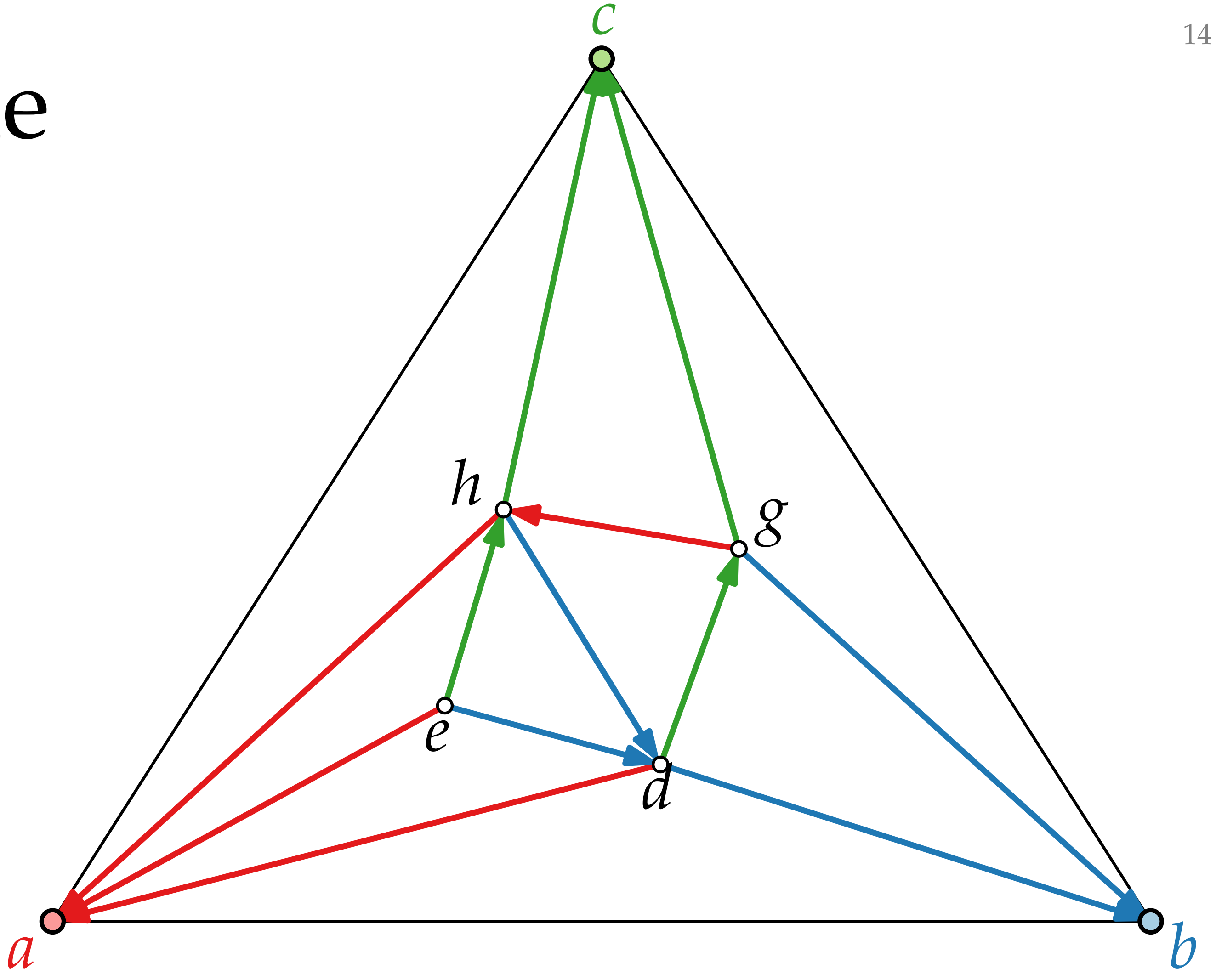

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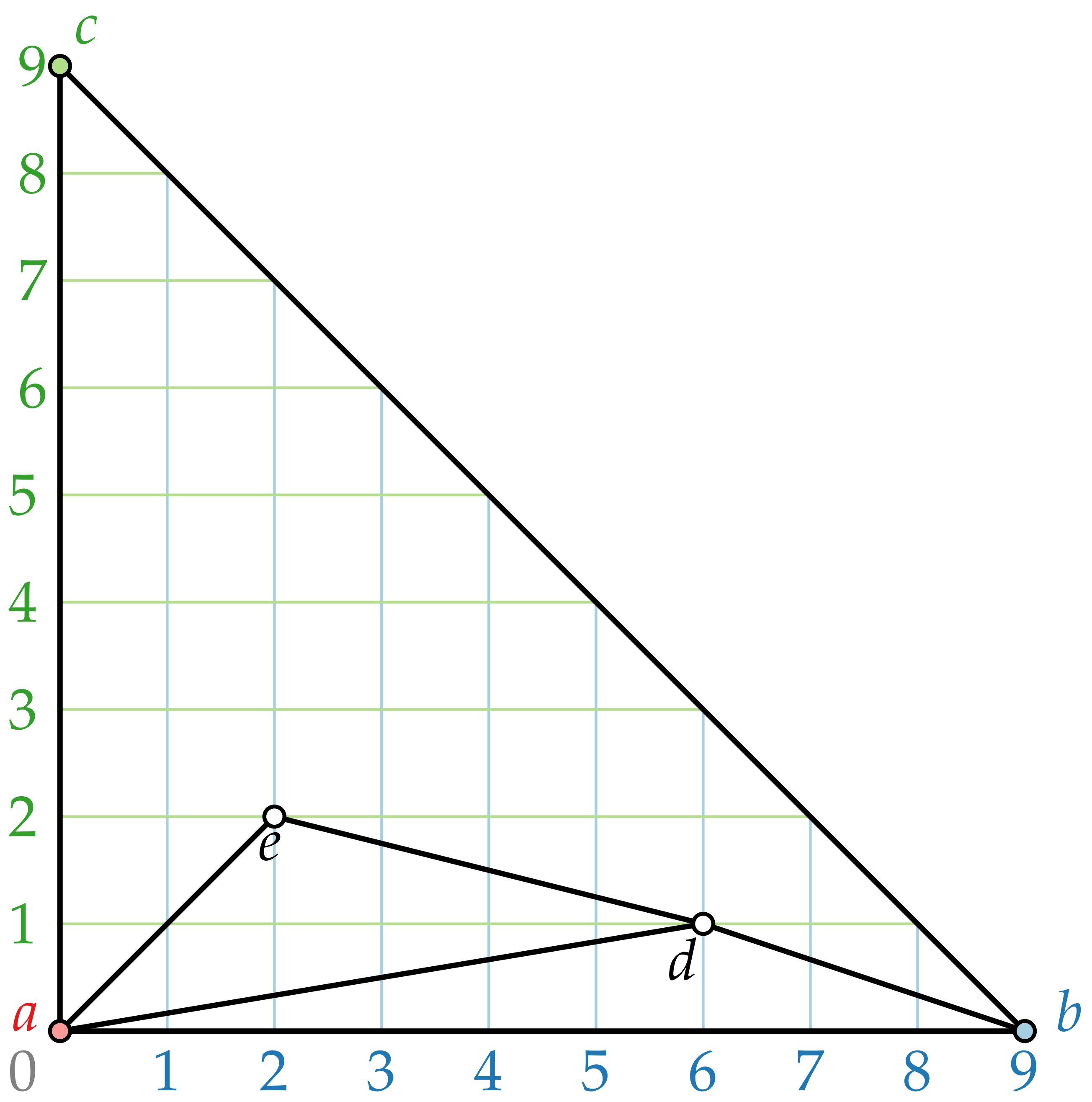

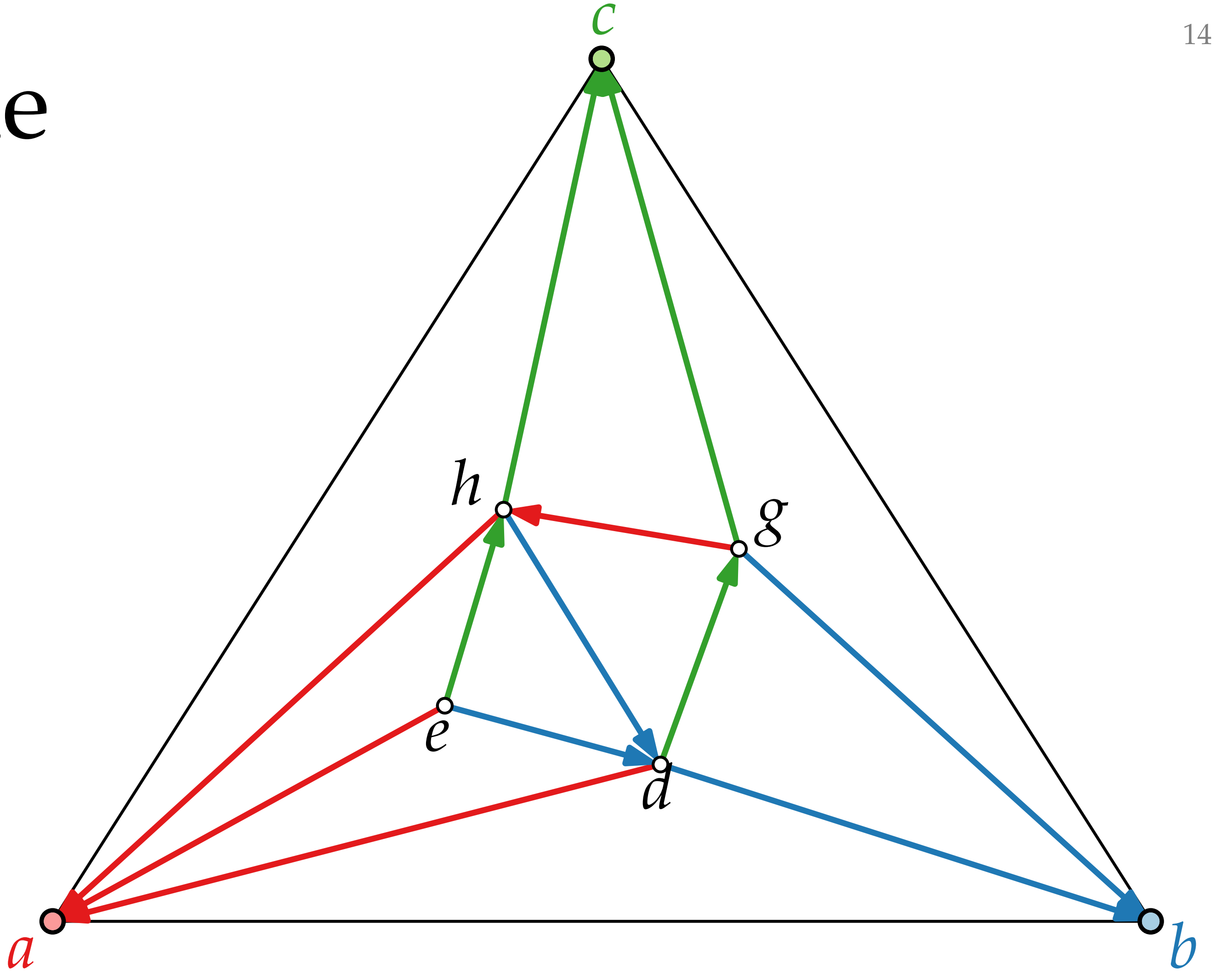

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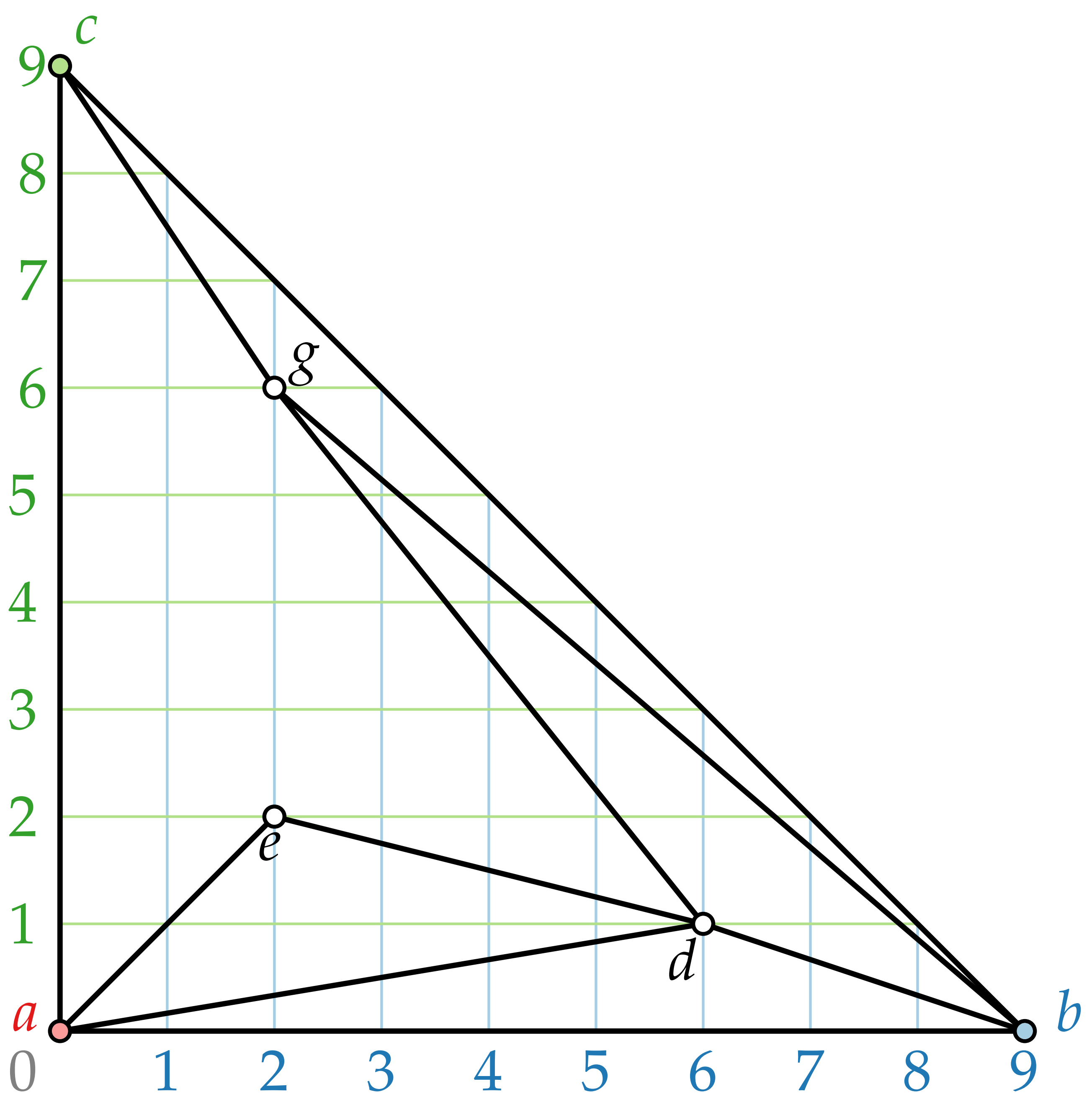

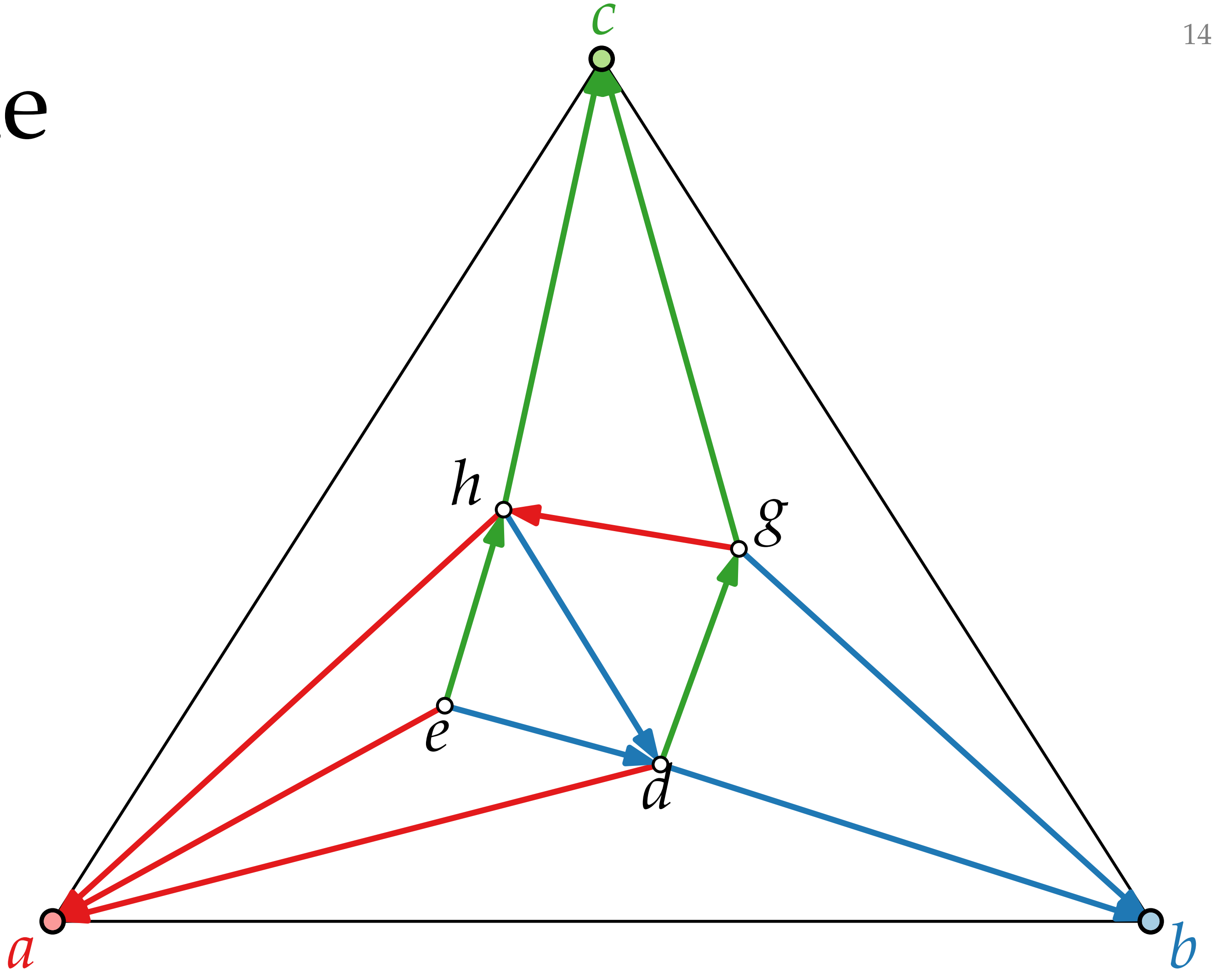

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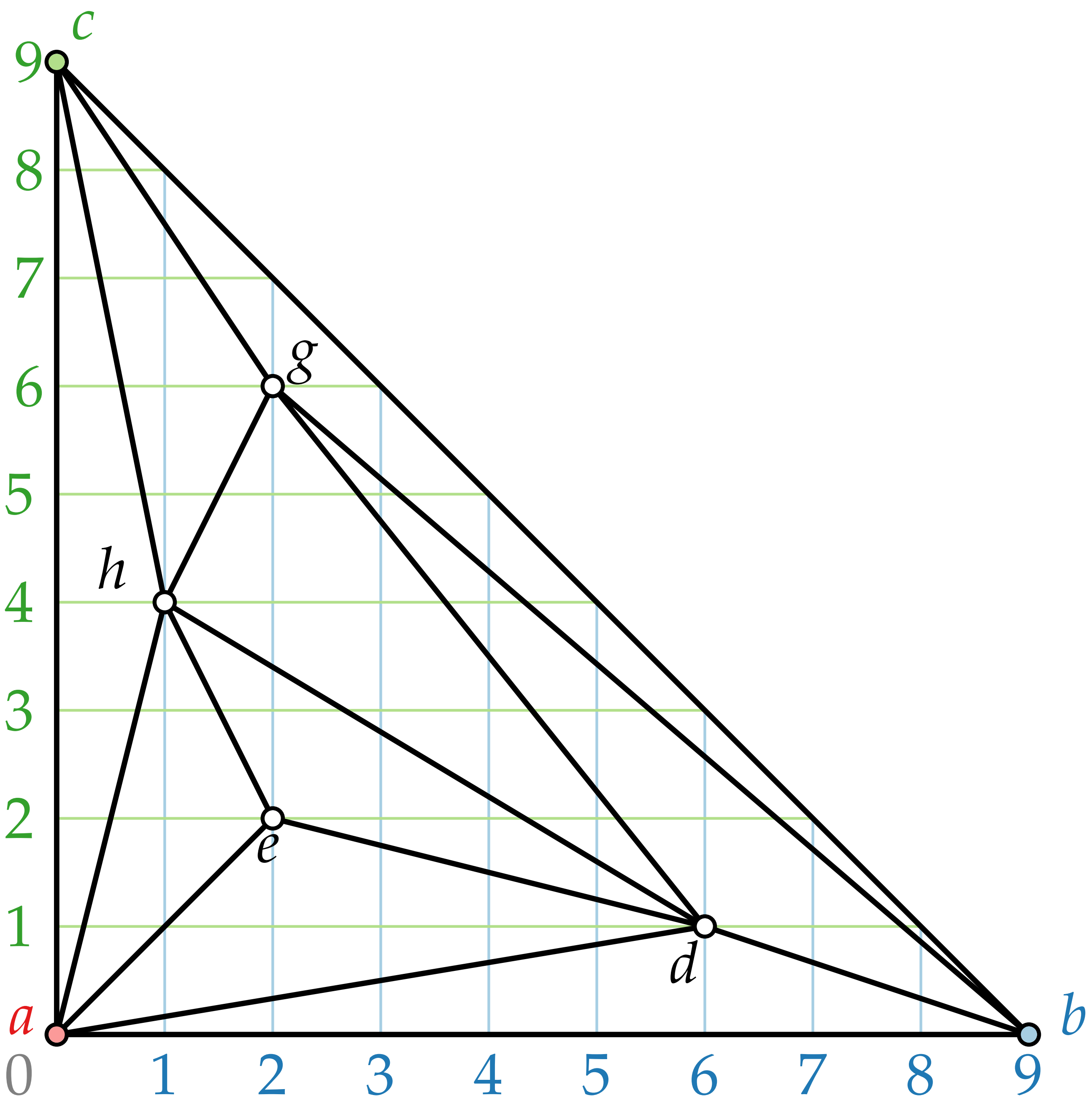

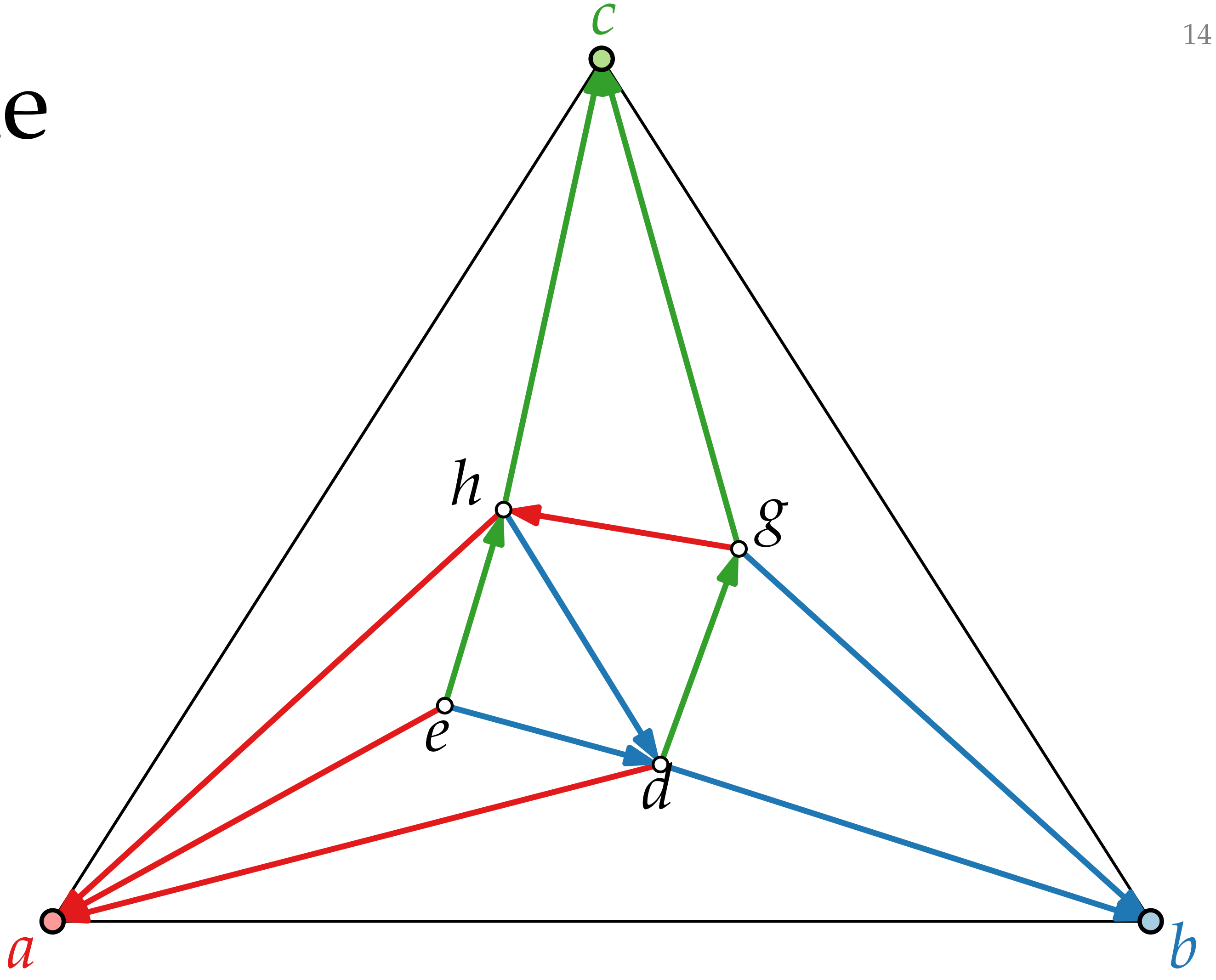

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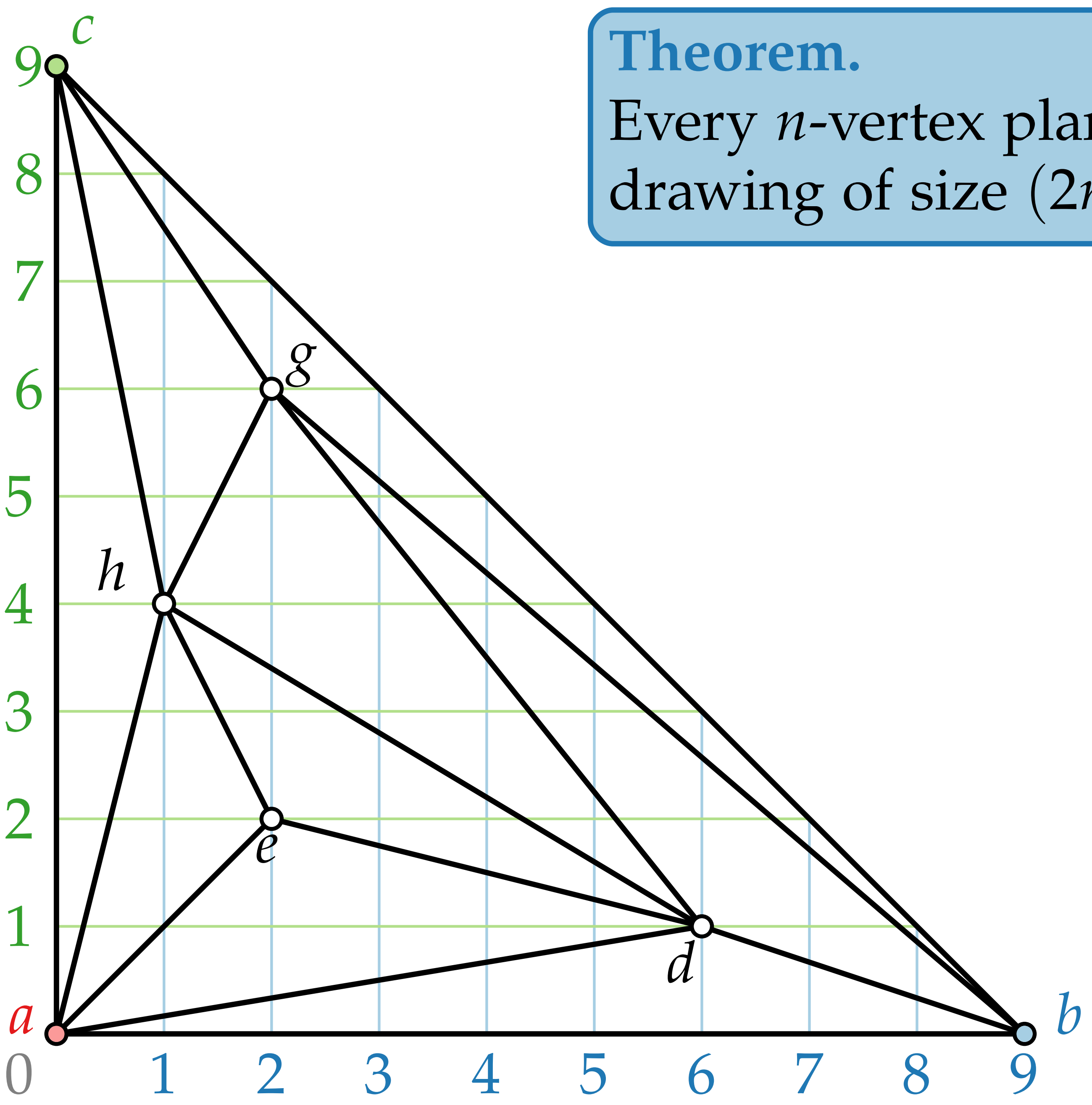
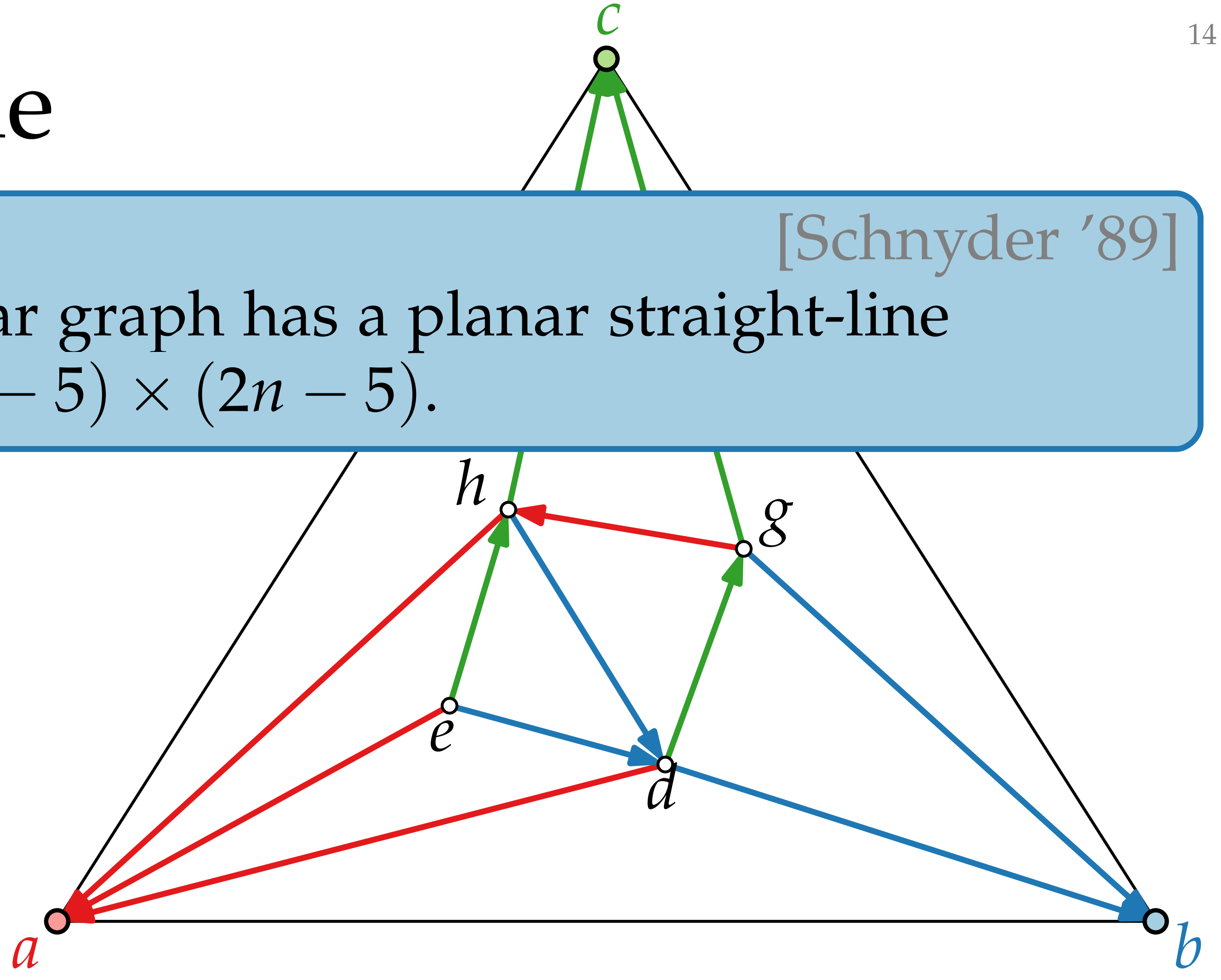


Theorem. [Schnyder '89]
Every n-vertex planar graph has a planar straight-line drawing of size $(2n-5) \times (2n-5)$.



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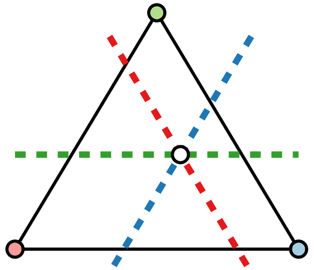
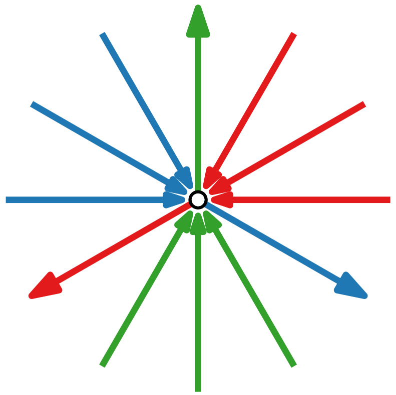
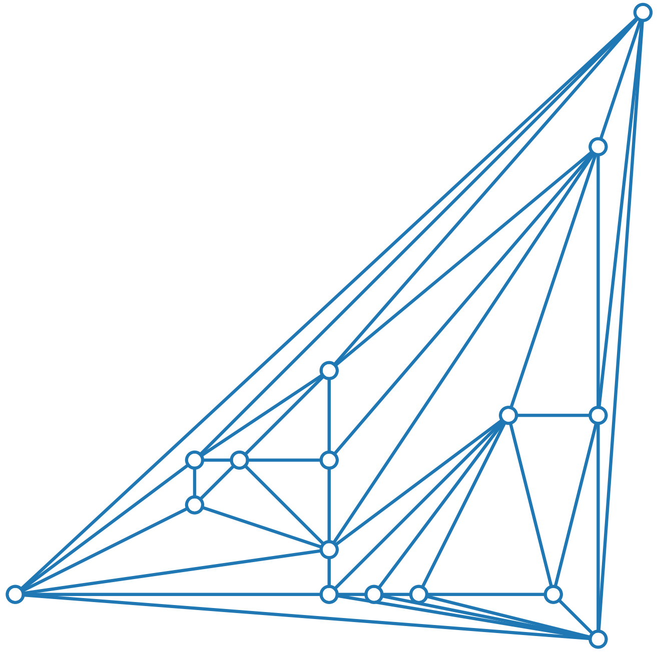
Universität Trier



Visualization of Graphs



Lecture 5:
Straight-Line Drawings of Planar Graphs II: Schnyder Woods



Part IV:
Weak Barycentric Representation

Philipp Kindermann

Weak Barycentric Representation

A **weak barycentric representation** of a graph $G = (V, E)$ is an assignment of barycentric coordinates to V:

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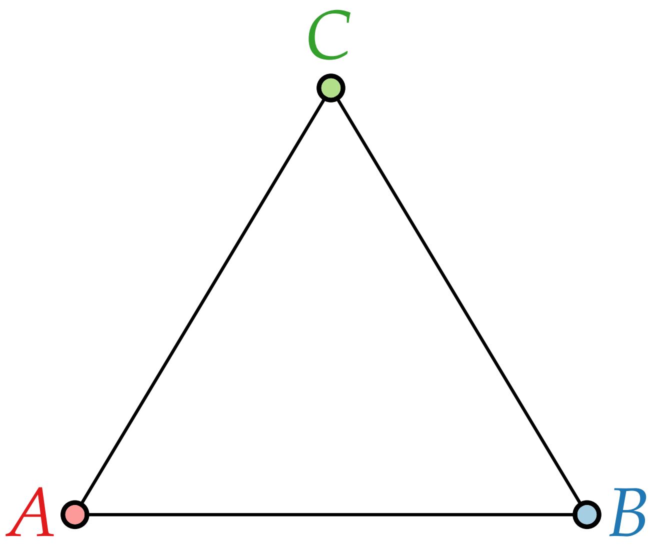

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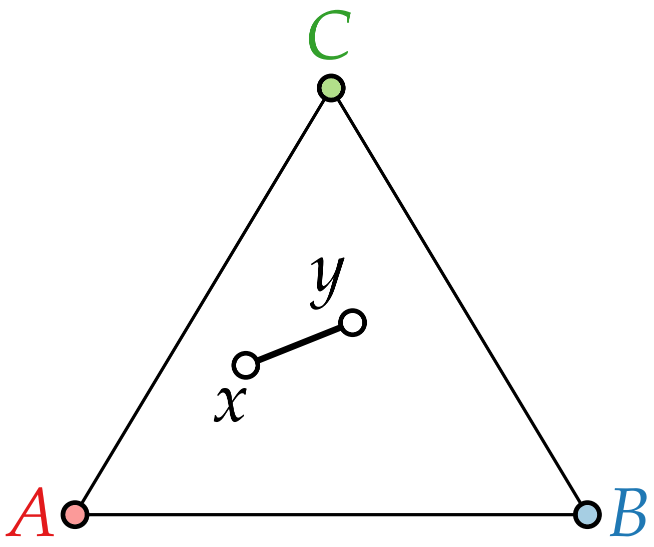

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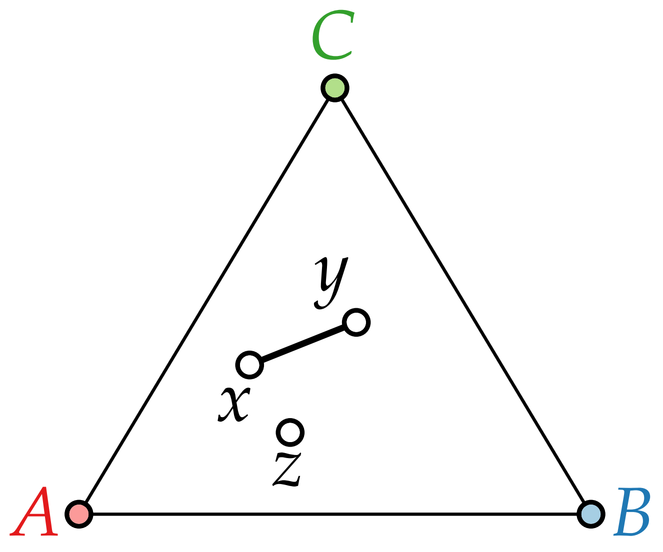

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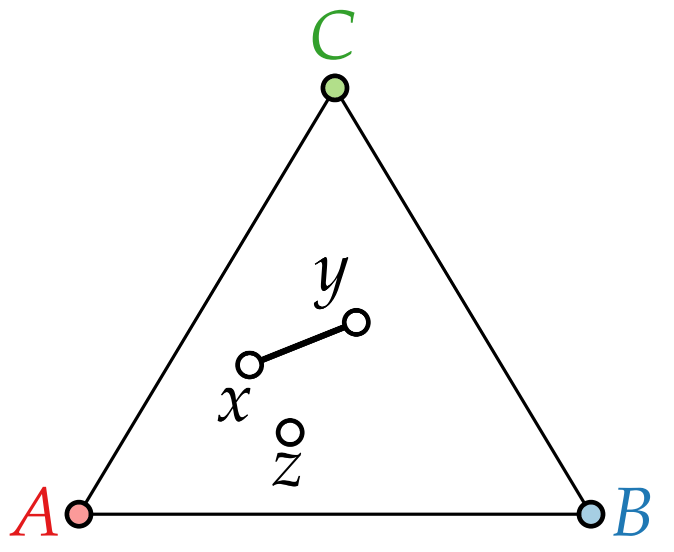

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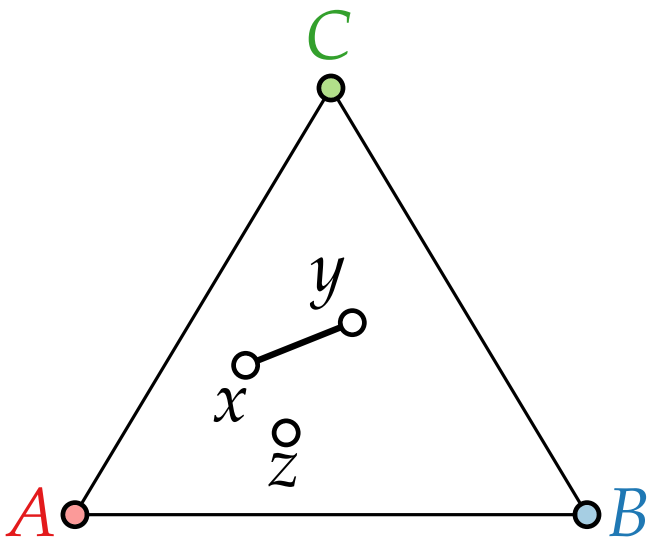

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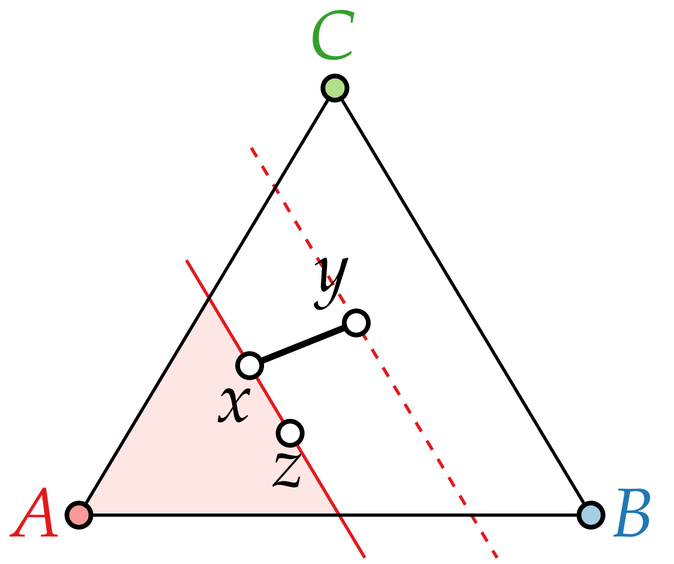

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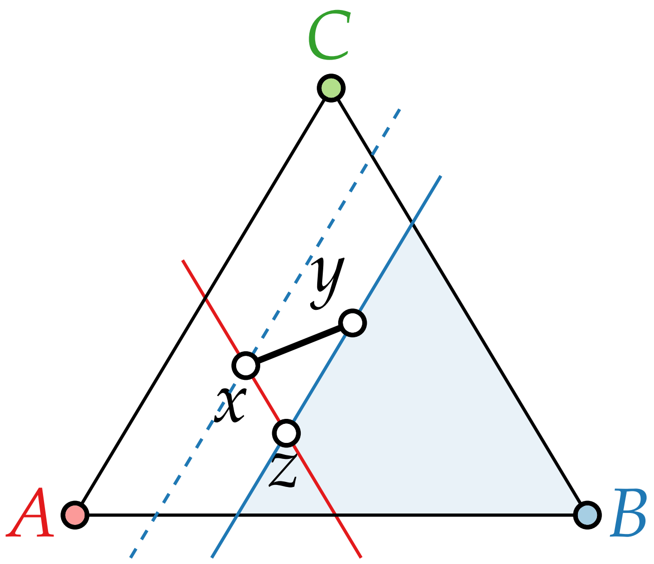

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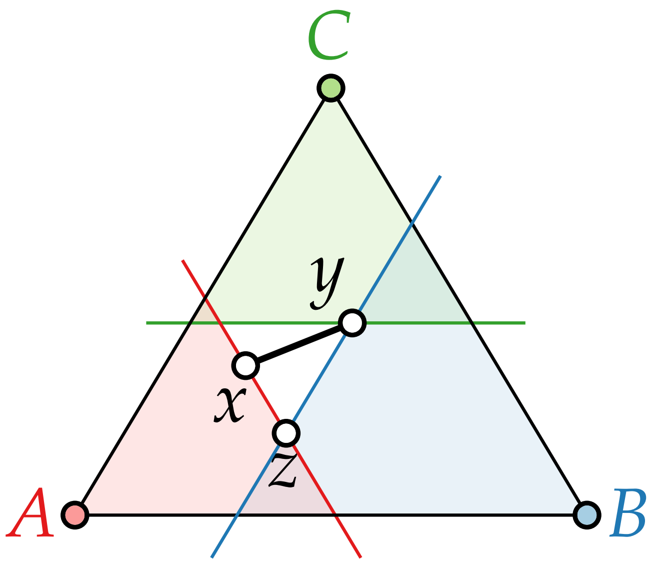

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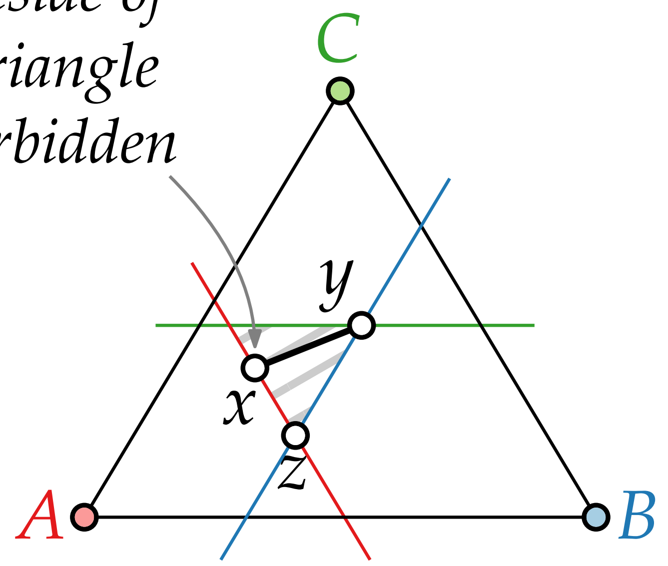

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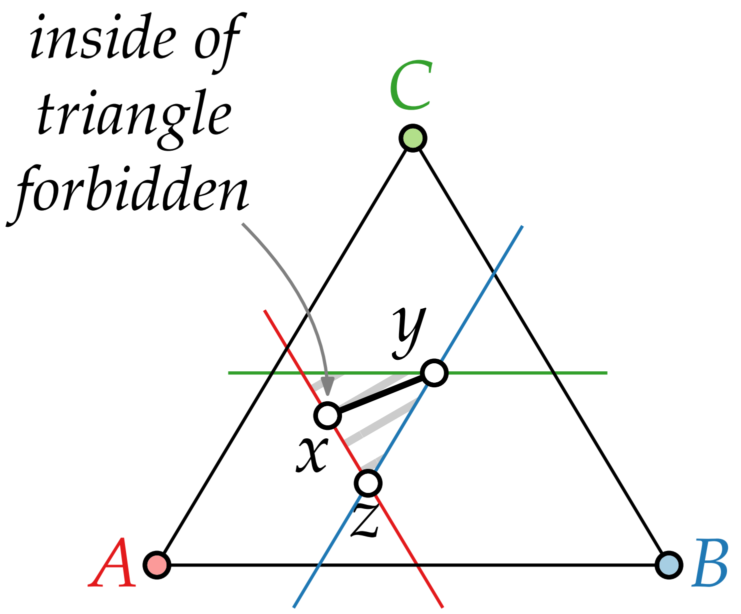

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Lemma.
For a weak barycentric representation $\phi : v \mapsto (v_1, v_2, v_3)$ and a triangle A, B, C, the mapping

$$f\colon v \in V \mapsto v_1 A + v_2 B + v_3 C$$

gives a **planar** drawing of G inside $\triangle ABC$.

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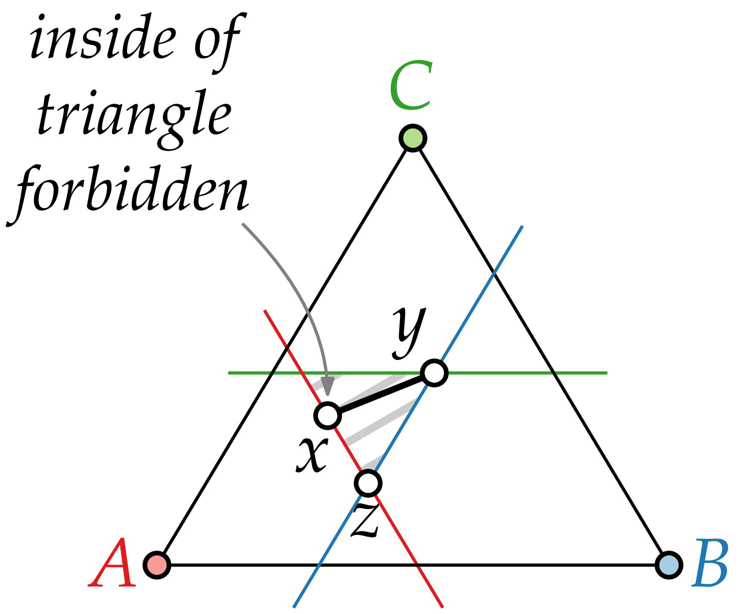
(W2) for each $xy \in E$ and each $z \in V \setminus \{x, y\}$ there exists $k \in \{1, 2, 3\}$ with $(x_k, x_{k+1}) <_{\text{lex}} (z_k, z_{k+1})$ and $(y_k, y_{k+1}) <_{\text{lex}} (z_k, z_{k+1})$.



i.e., either $y_k < z_k$ or $y_k = z_k$ and $y_{k+1} < z_{k+1}$

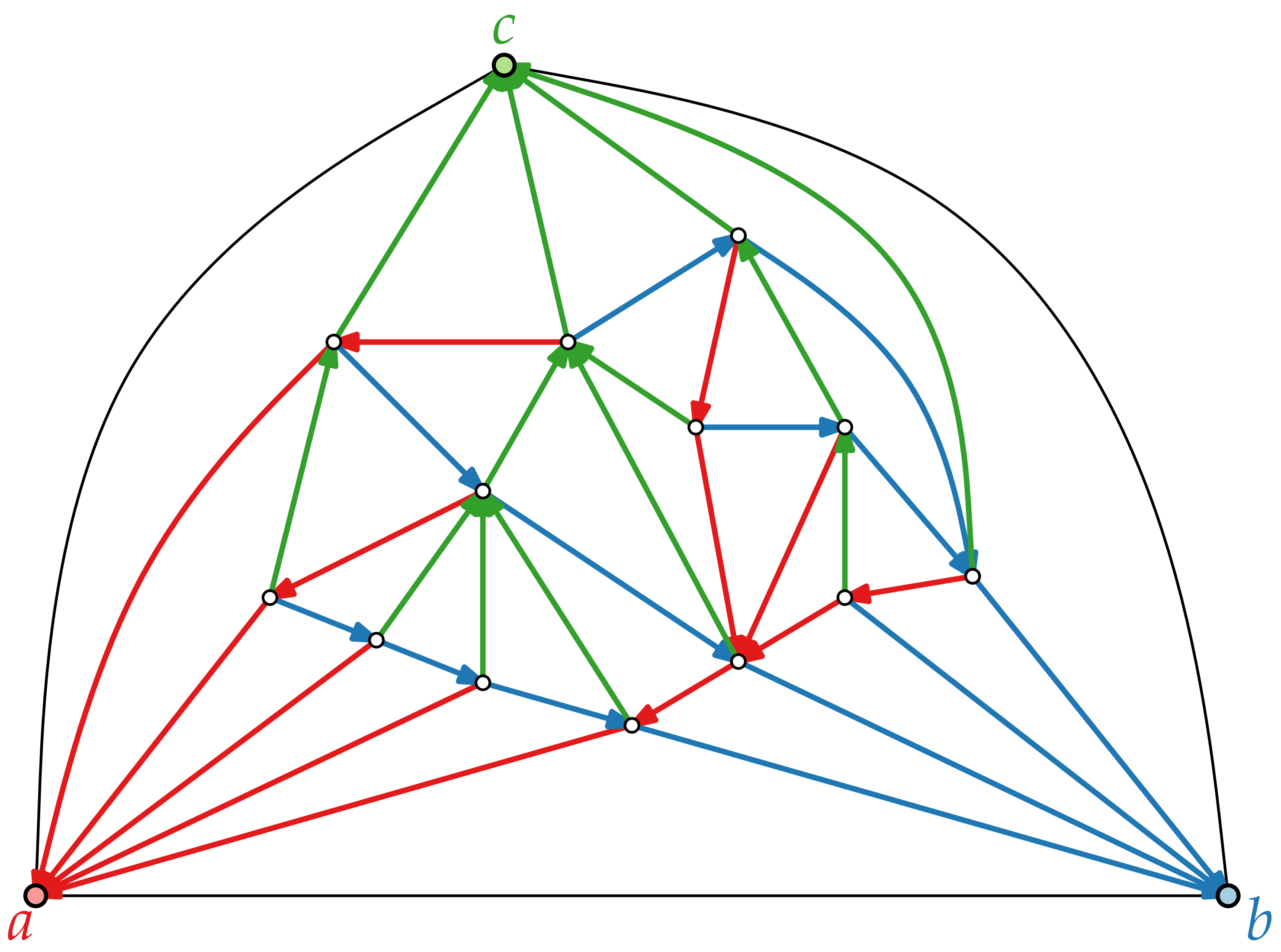
Lemma.
For a weak barycentric representation $\phi : v \mapsto (v_1, v_2, v_3)$ and a triangle A, B, C, the mapping

$$f\colon v \in V \mapsto v_1 A + v_2 B + v_3 C$$

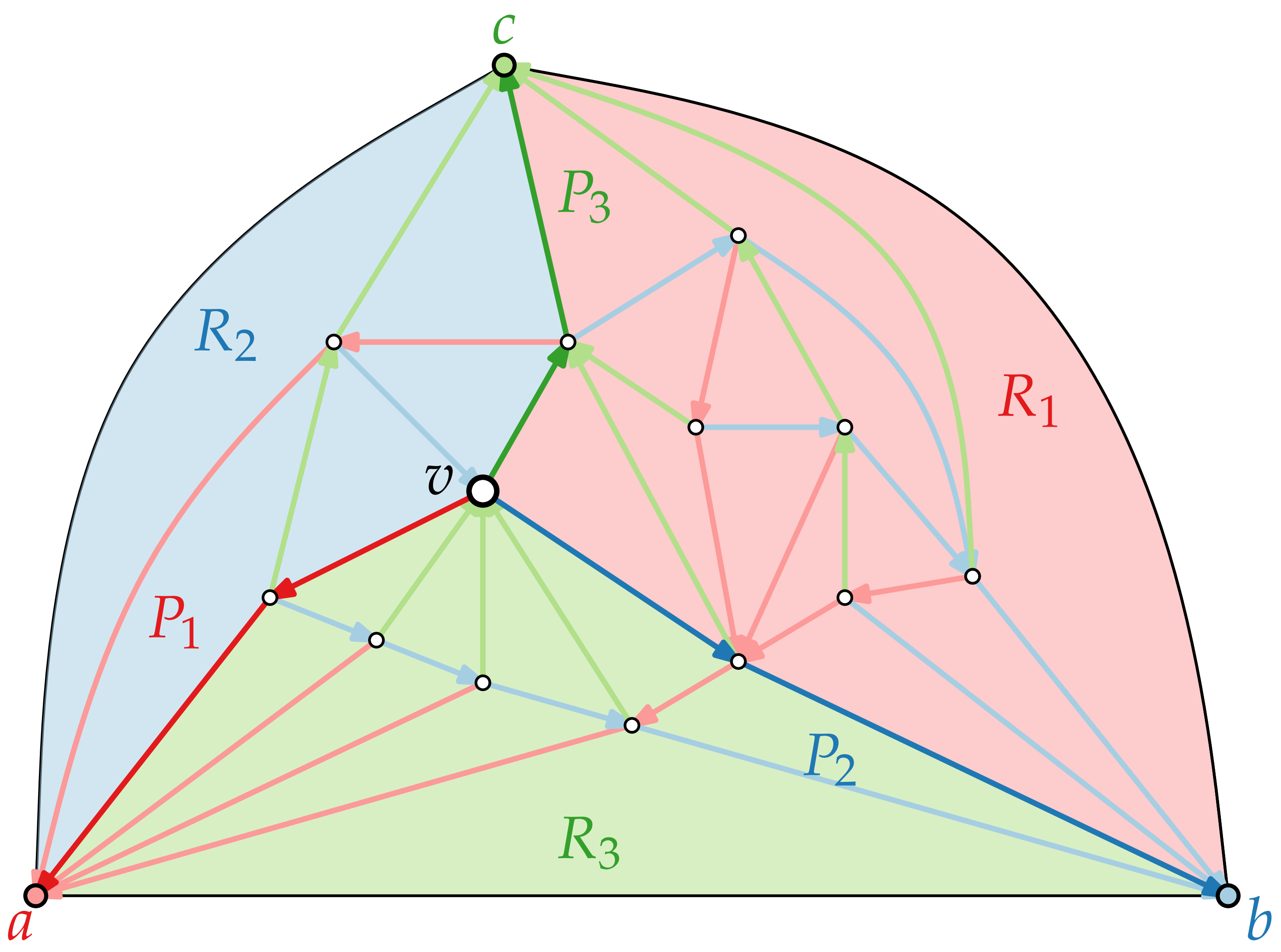
gives a **planar** drawing of G inside $\triangle ABC$.

Proof as exercise.

Counting Vertices



Counting Vertices



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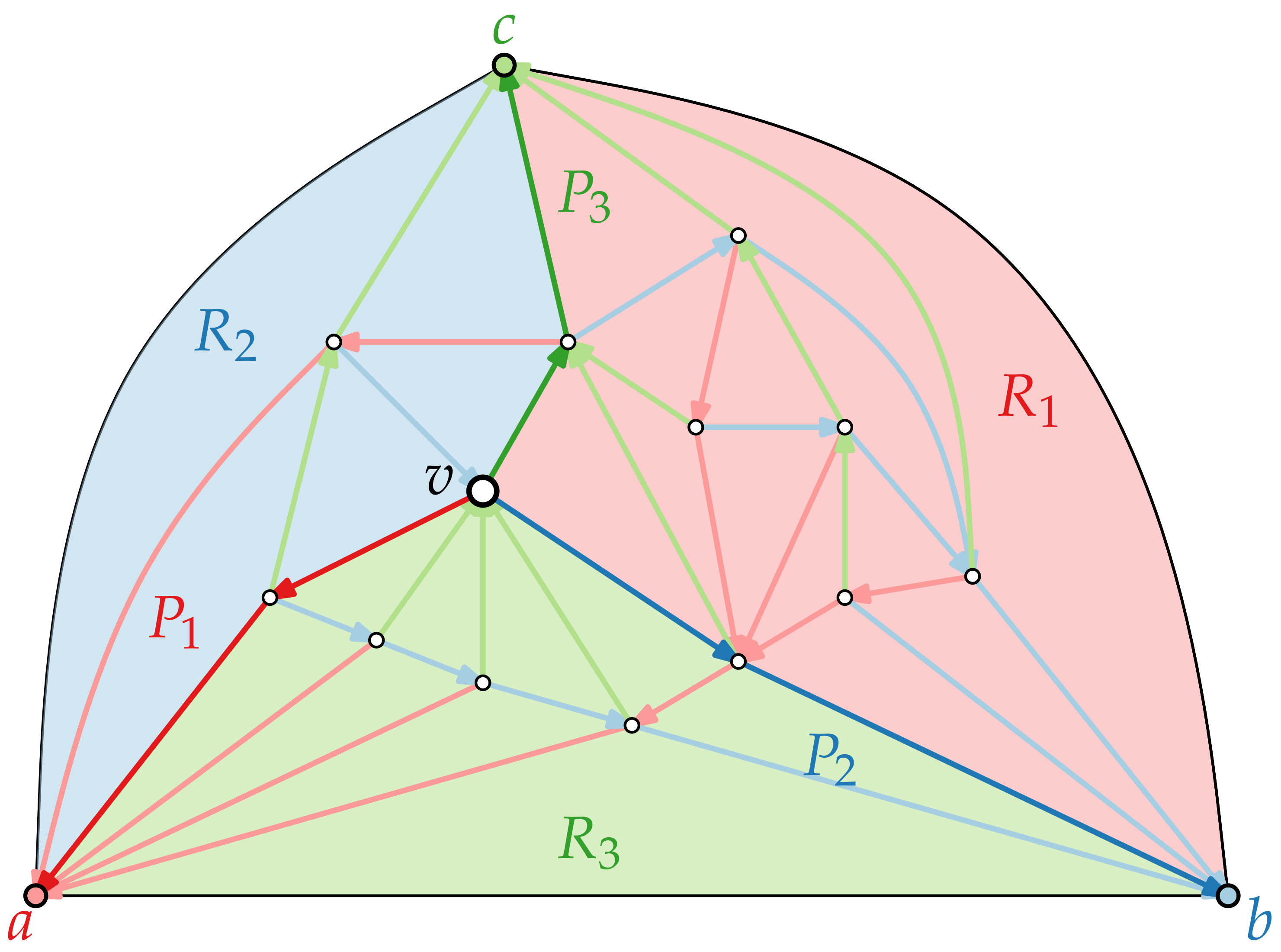

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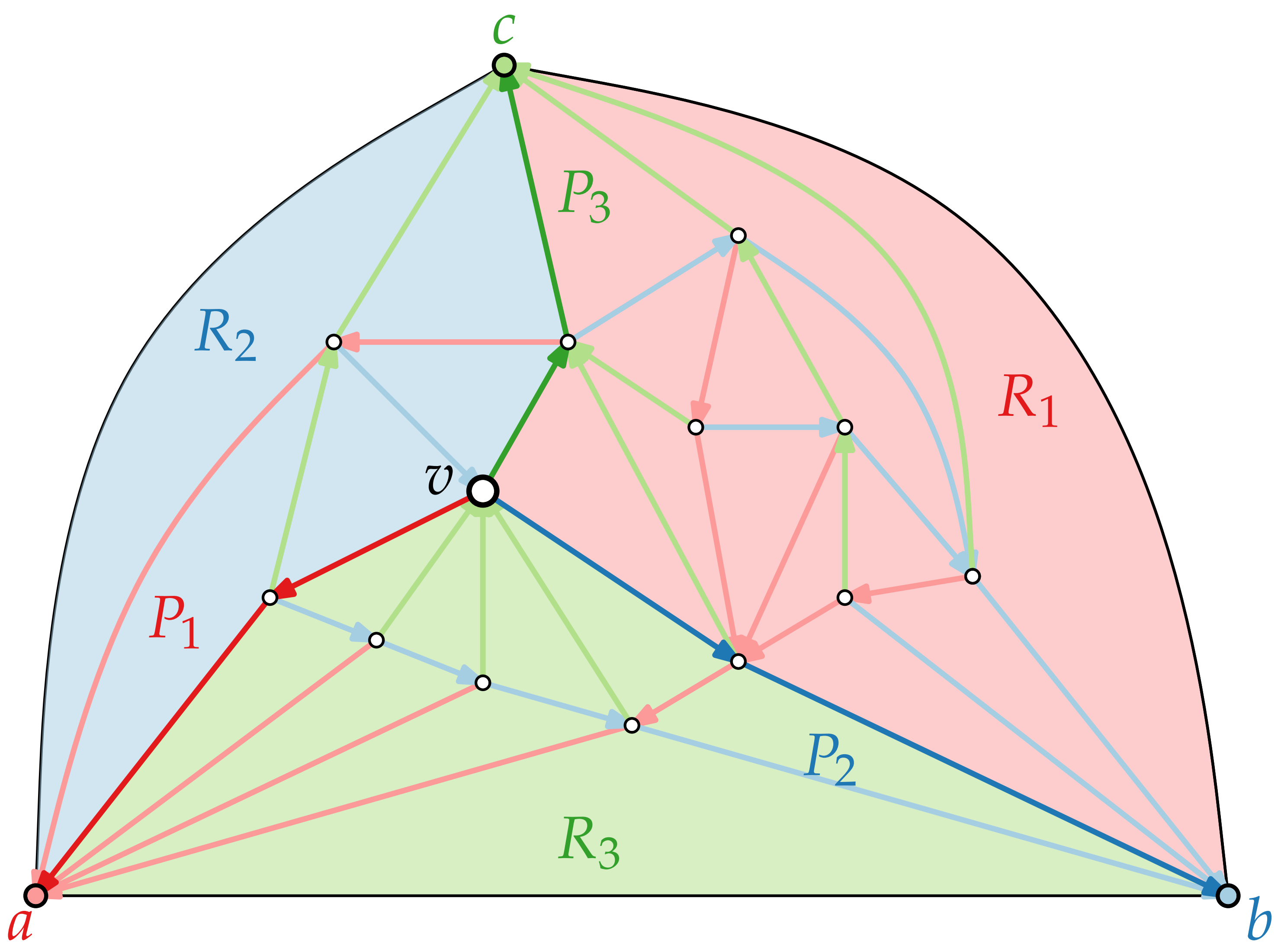
$v_i = |V(R_i(v))|$

Counting Vertices



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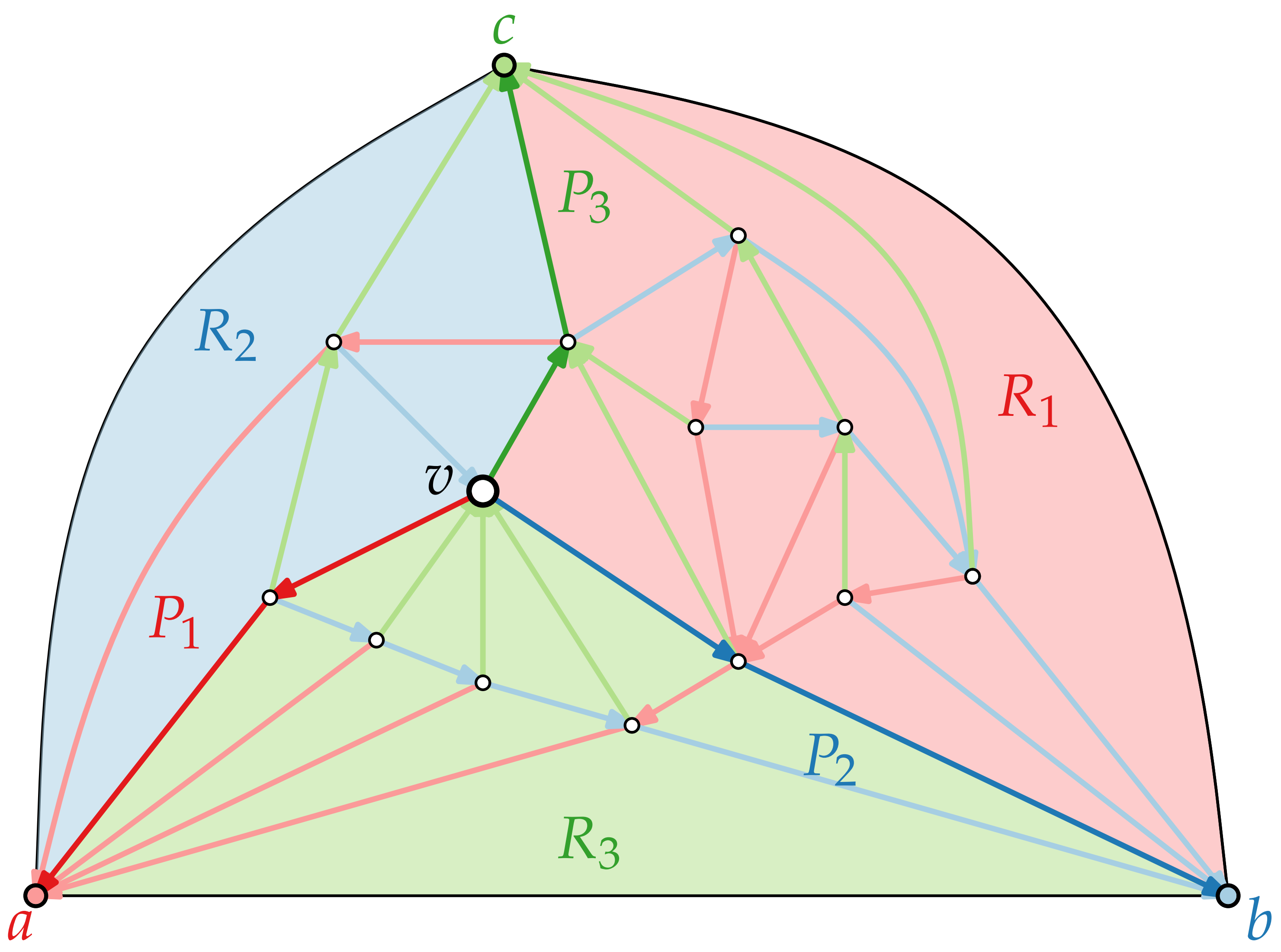
$v_i = |V(R_i(v))| - |P_{i-1}(v)|$

Counting Vertices



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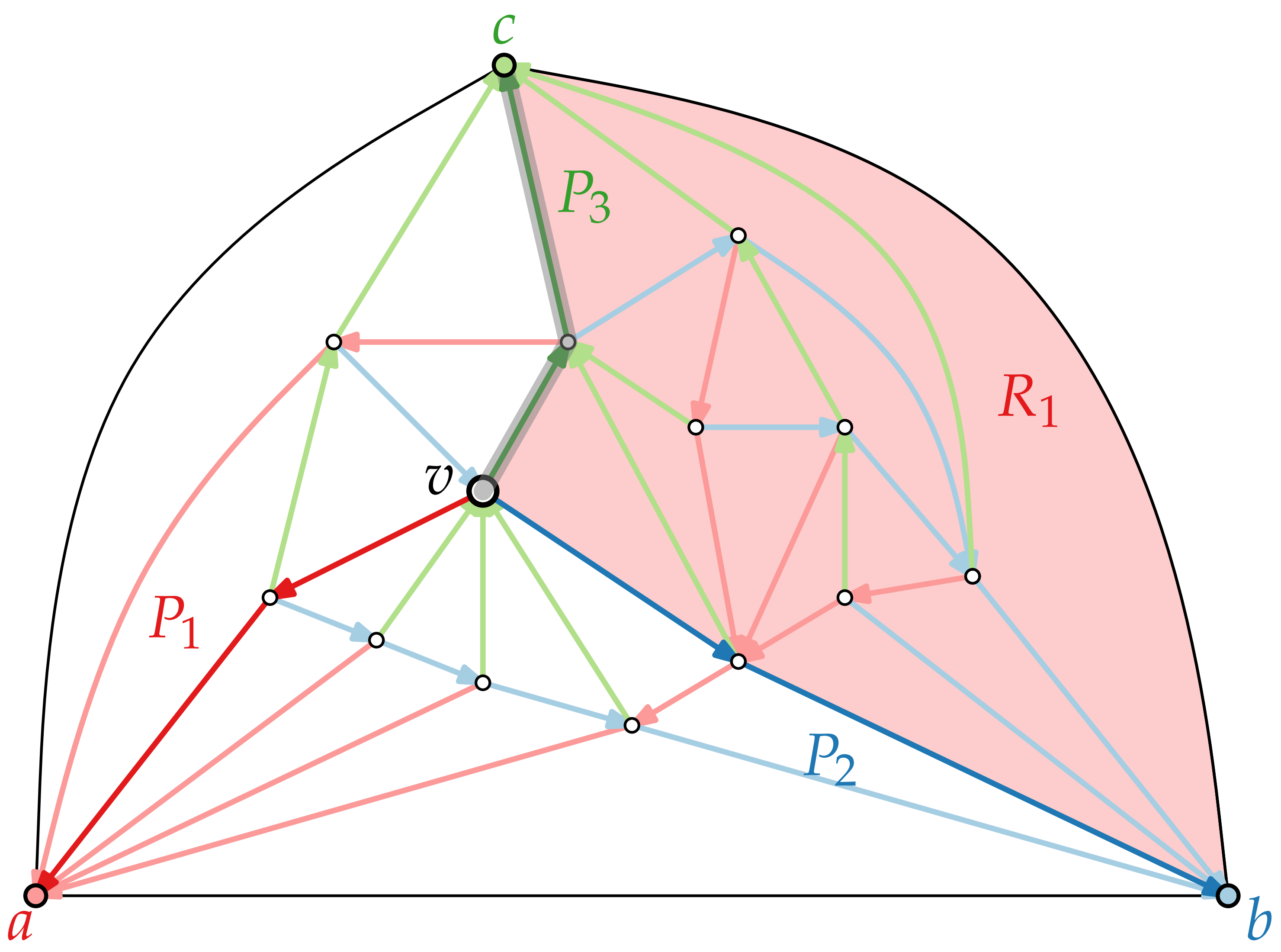
Counting Vertices



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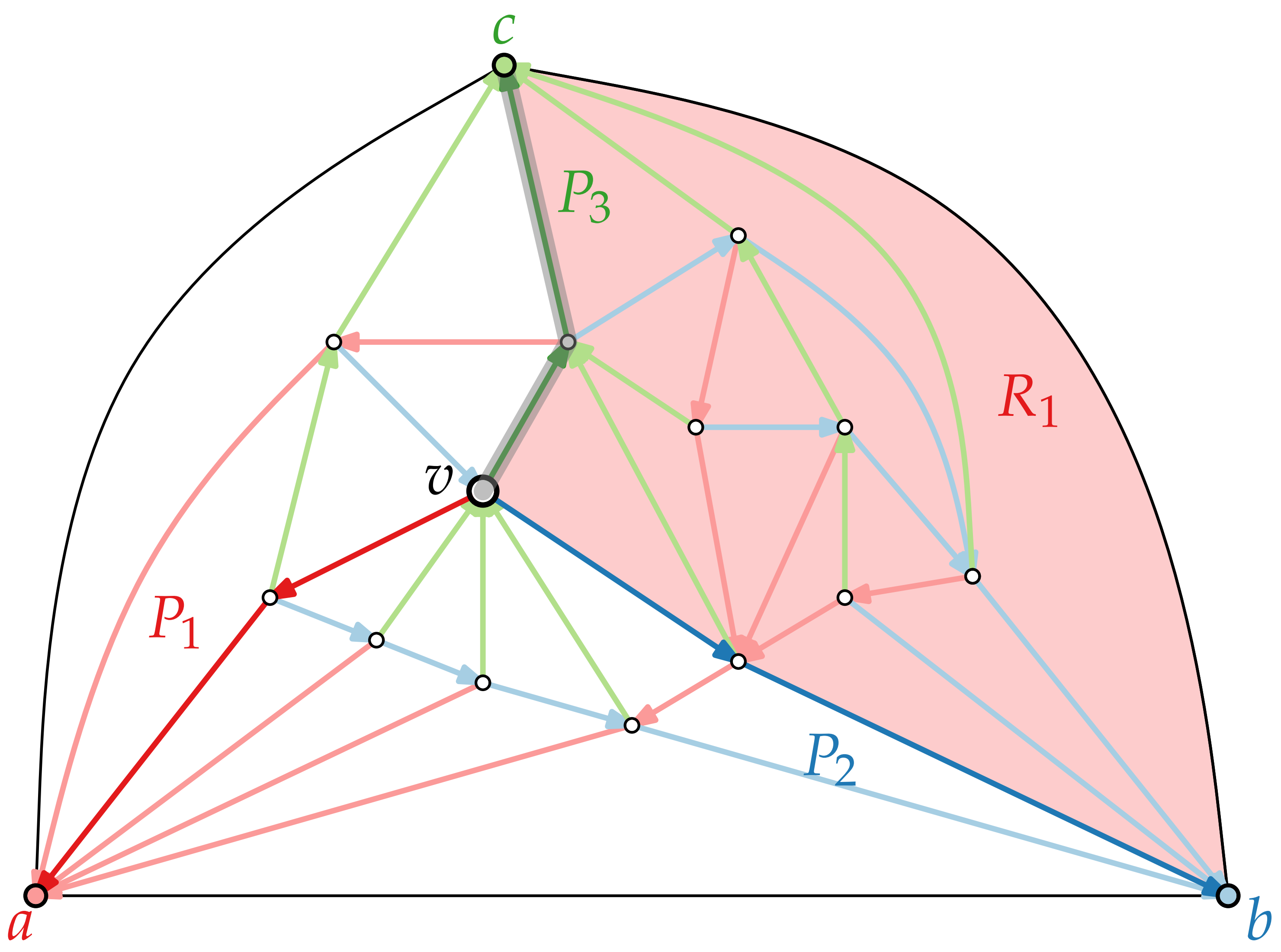

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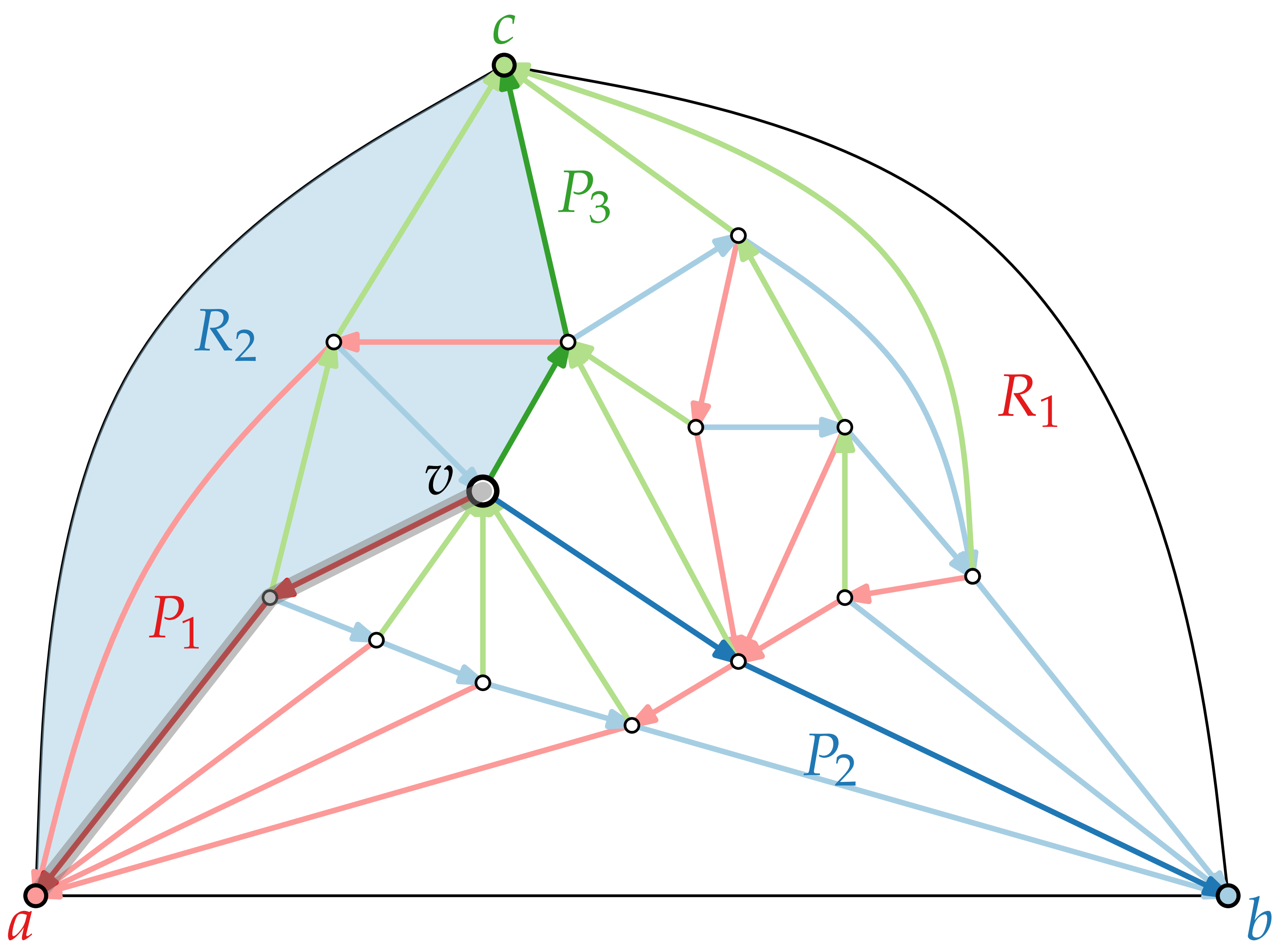
$v_1 = 10 - 3 = 7$

Counting Vertices



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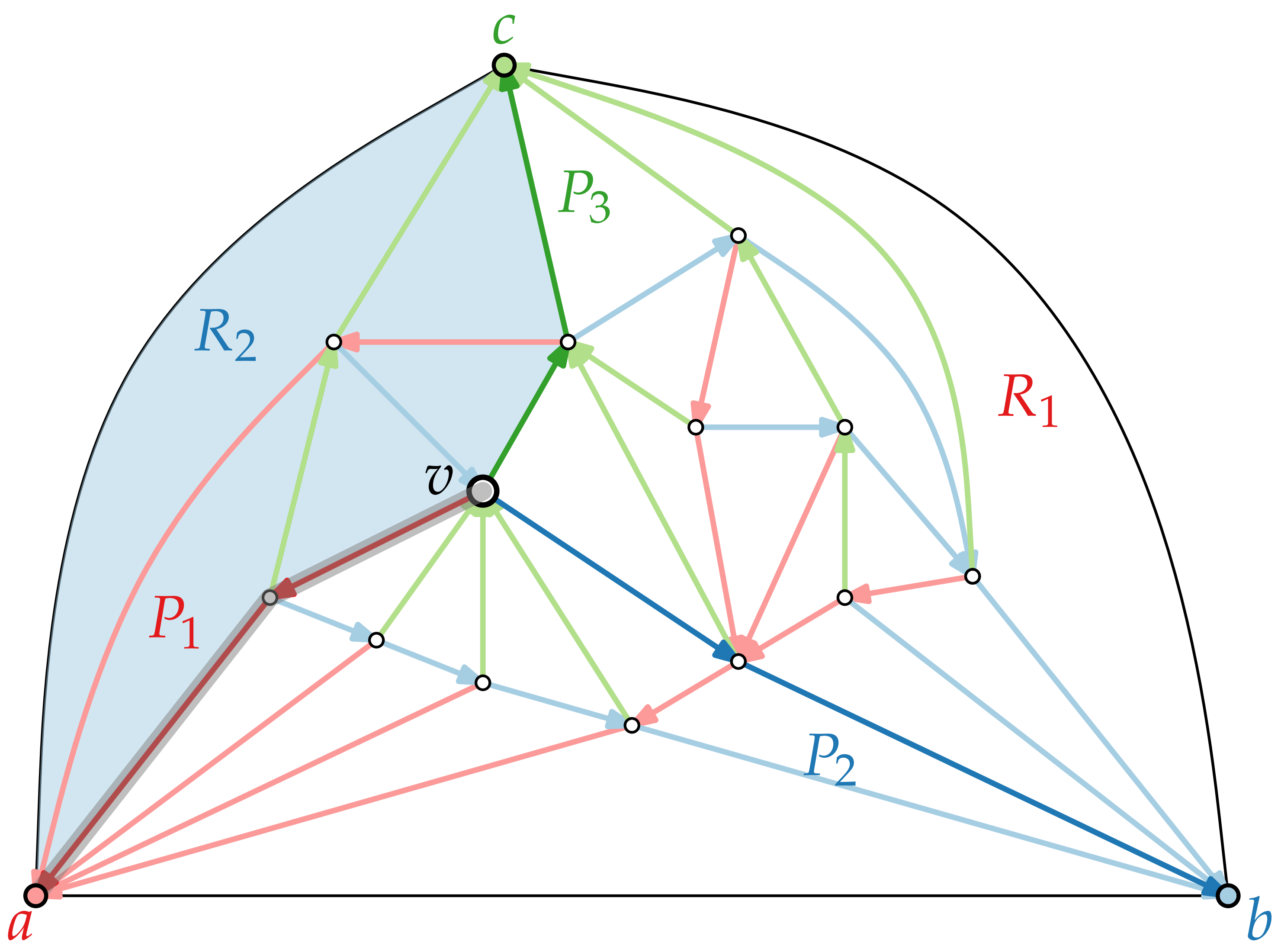
$v_2 =$

Counting Vertices



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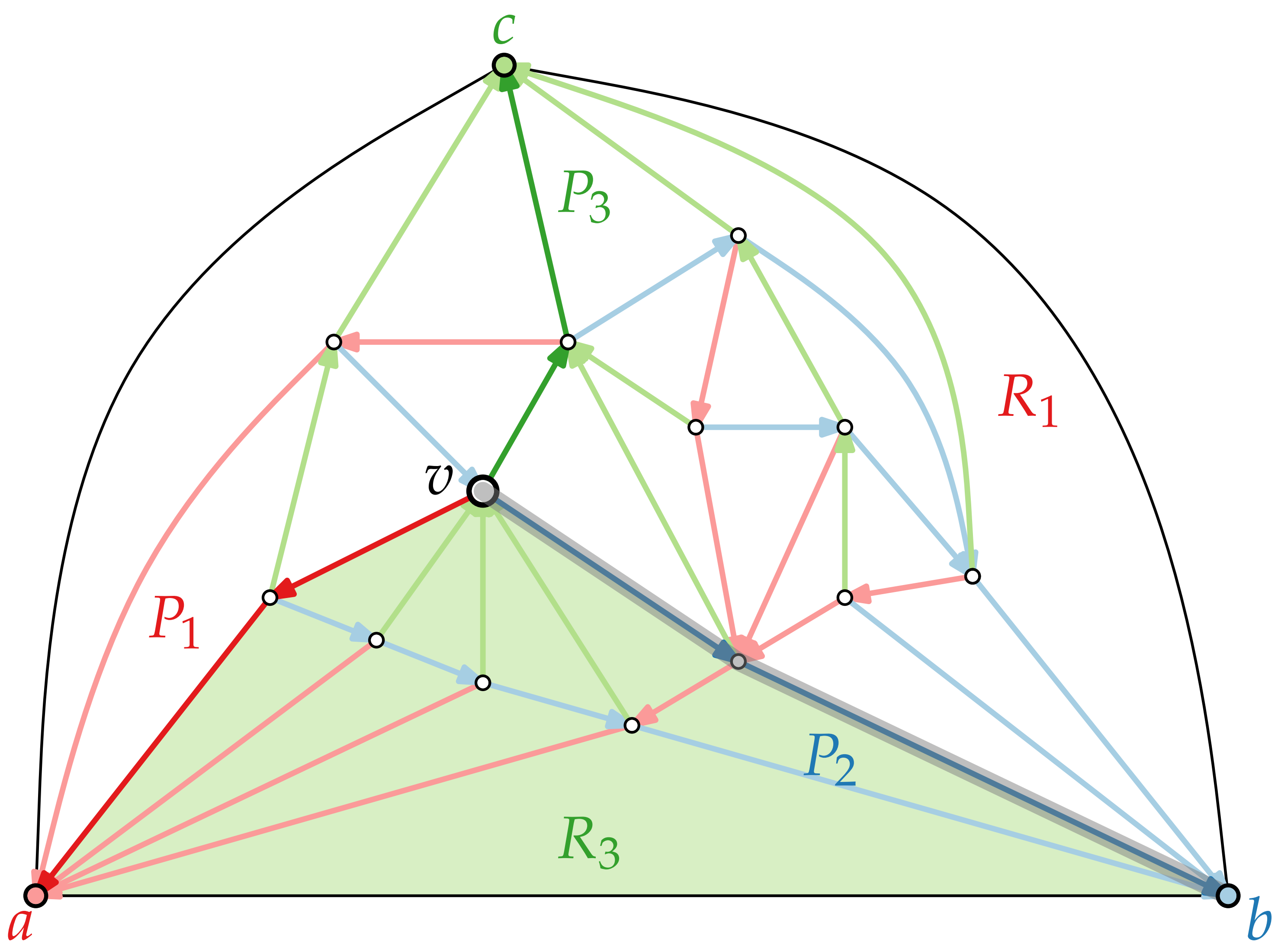
$v_1 = 10 - 3 = 7$

$v_2 = 6 - 3 = 3$

Counting Vertices



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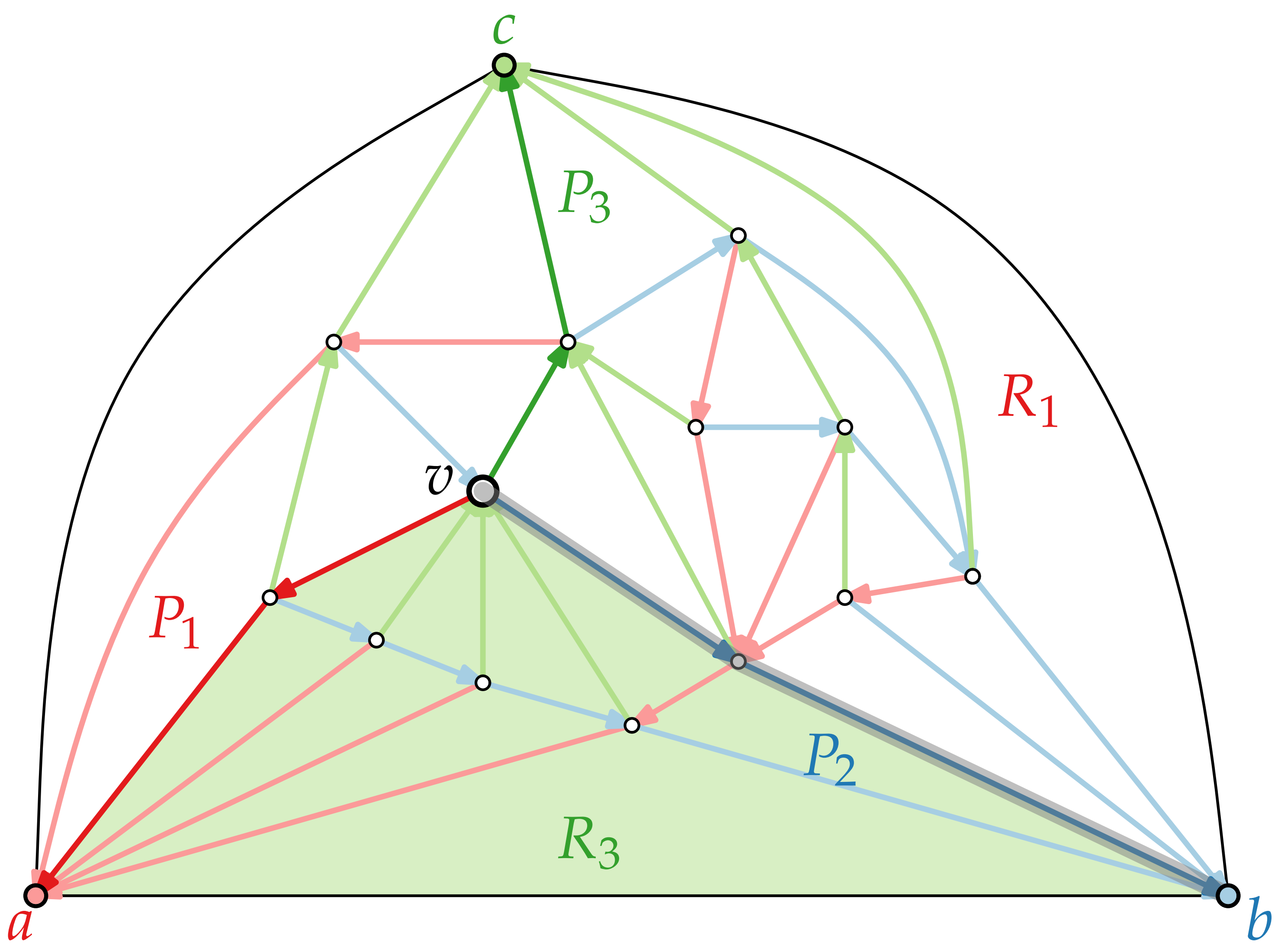

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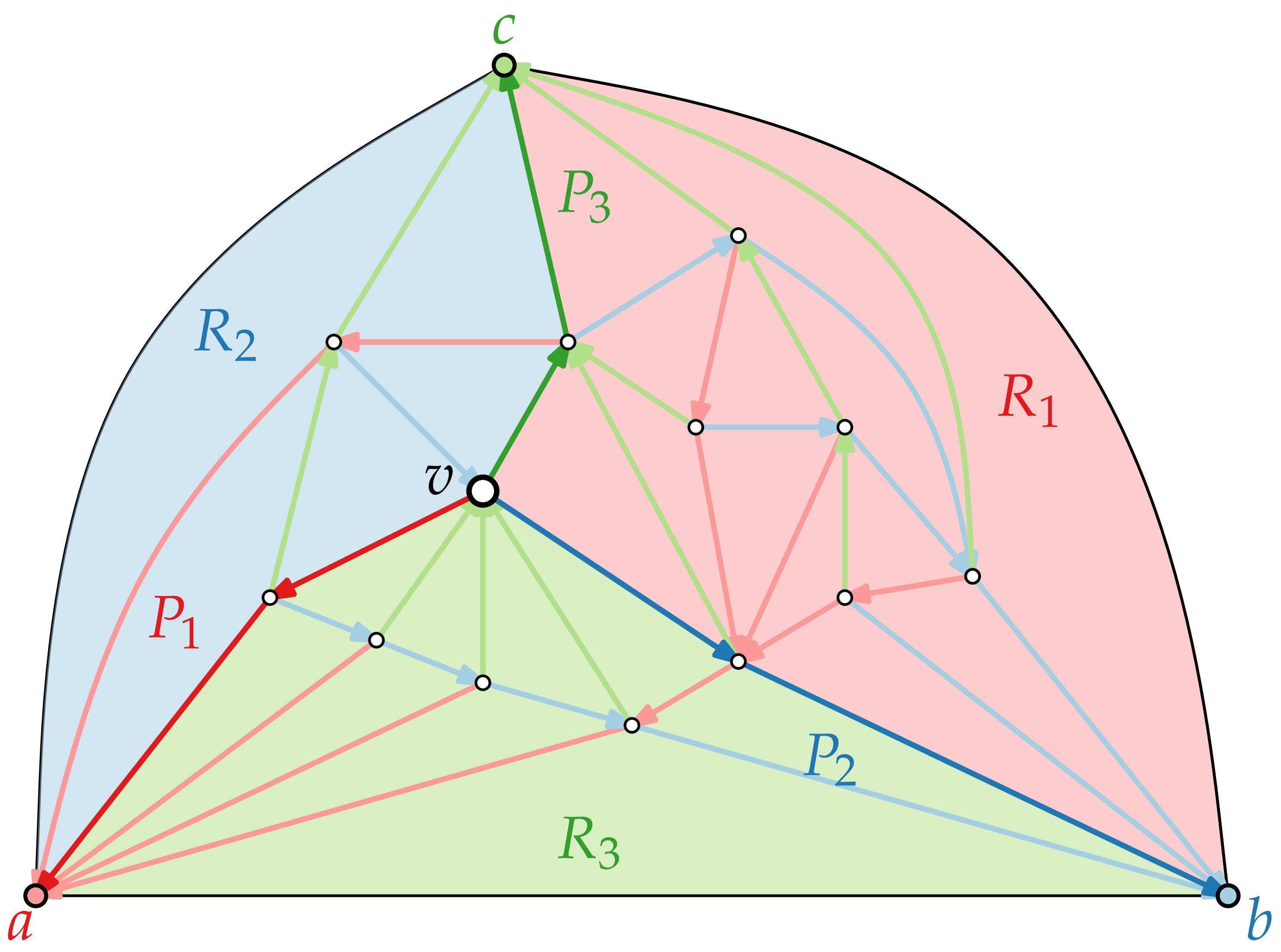
$v_3 = 8 - 3 = 5$

Counting Vertices



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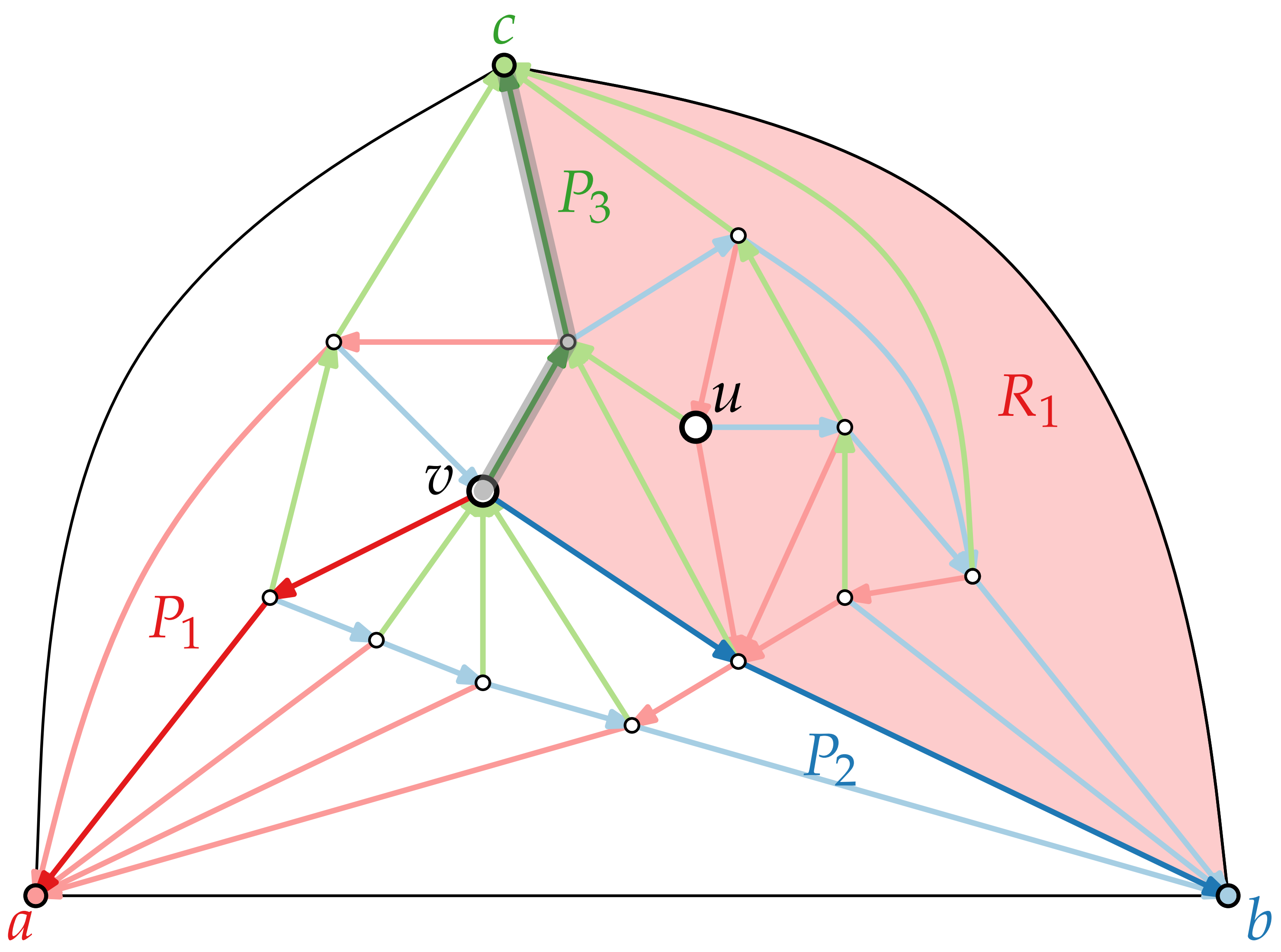
Lemma.

- For inner vertices $u \neq v$ it holds that $u \in R_i(v) \Rightarrow (u_i, u_{i+1}) <_{\text{lex}} (v_i, v_{i+1})$.

Counting Vertices



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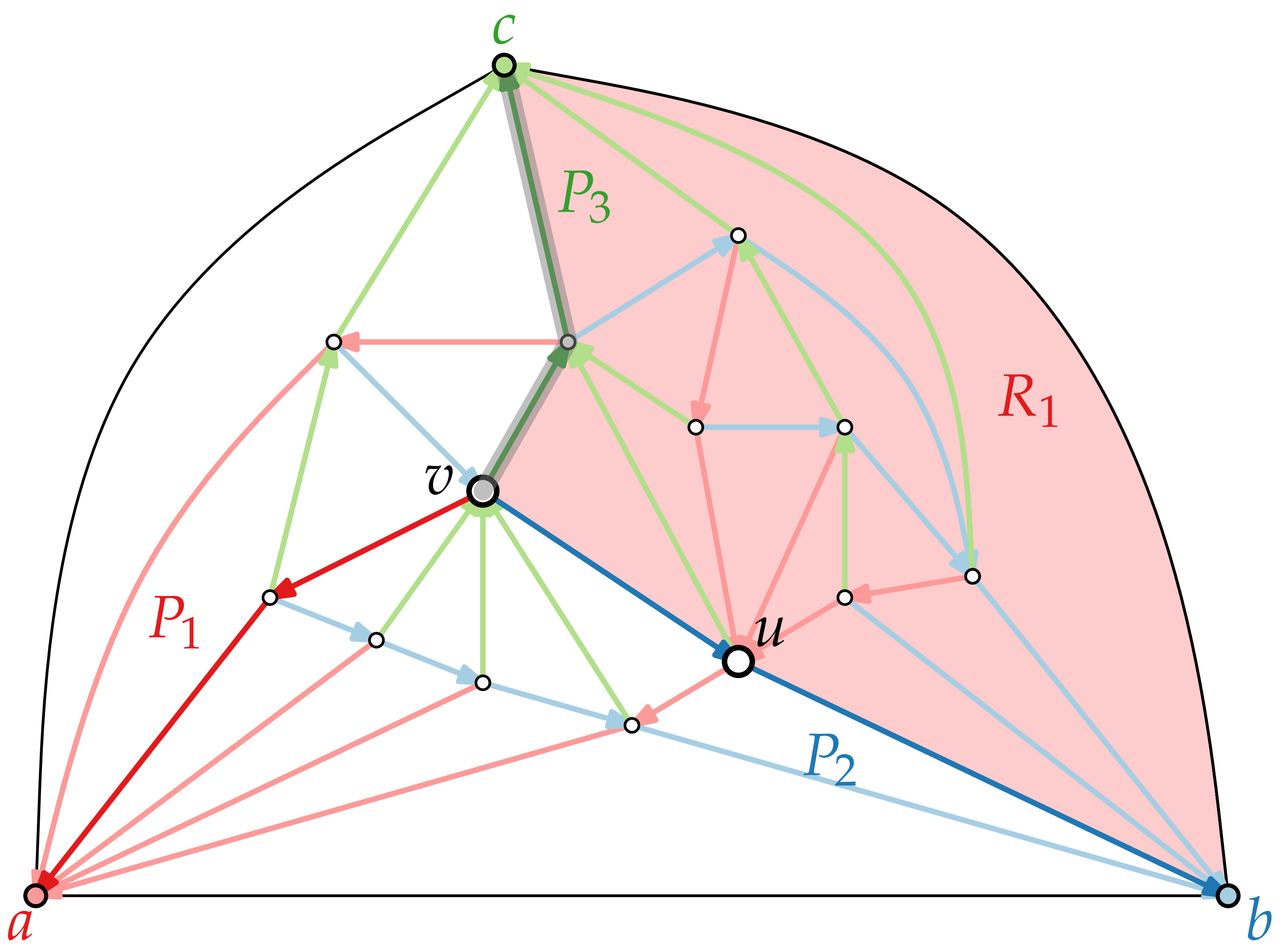

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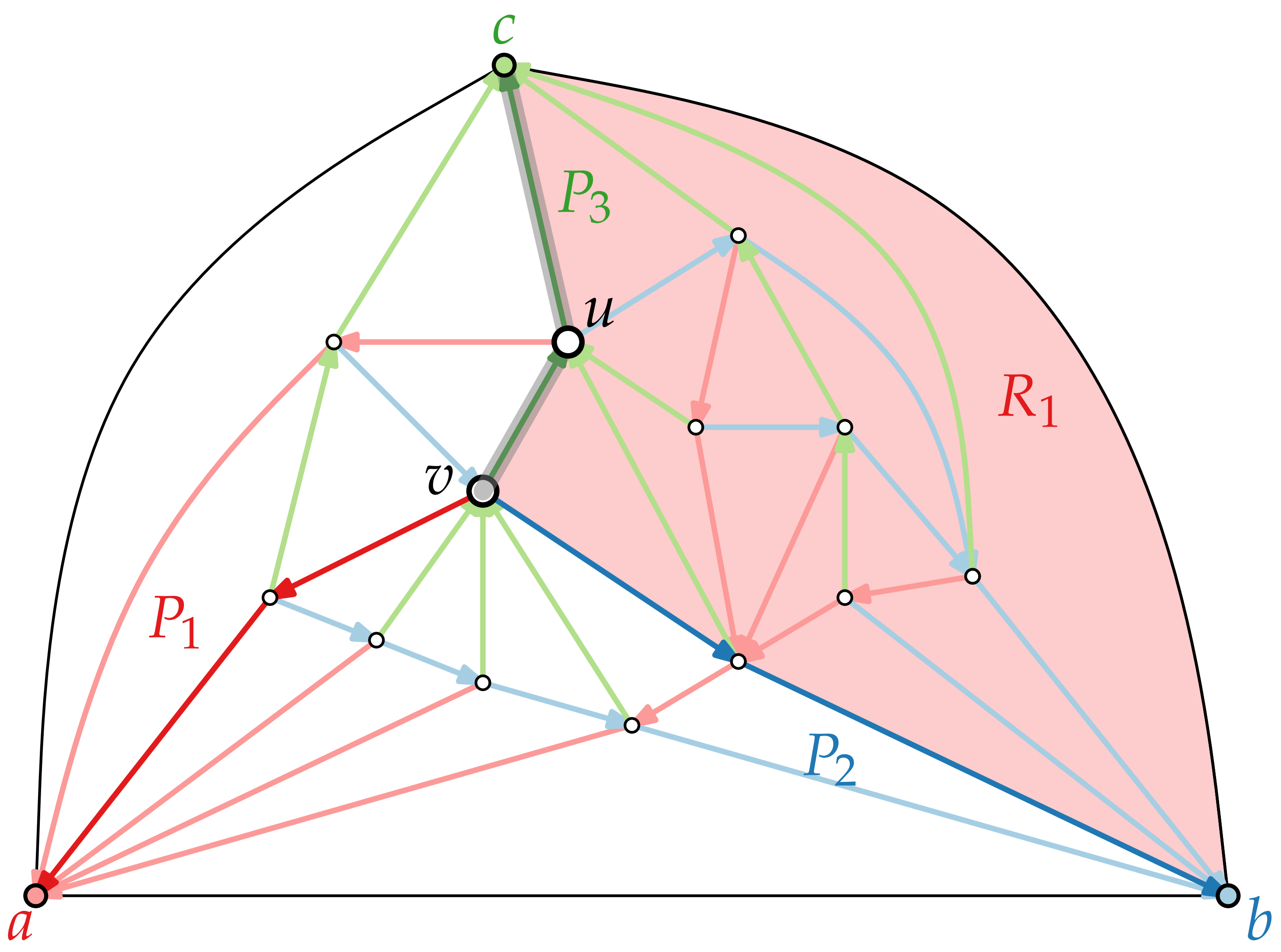

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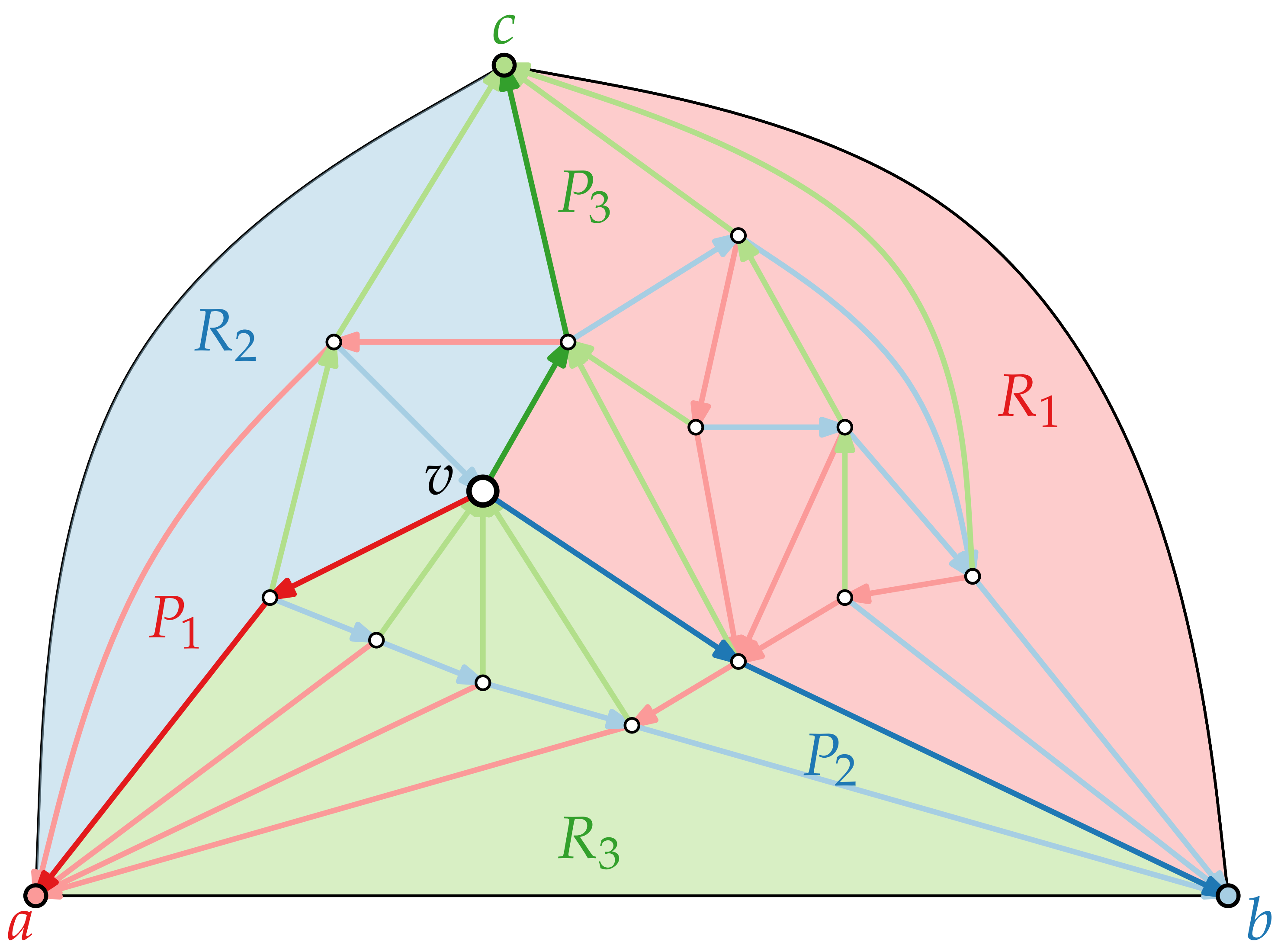

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- $v_1 + v_2 + v_3 =$

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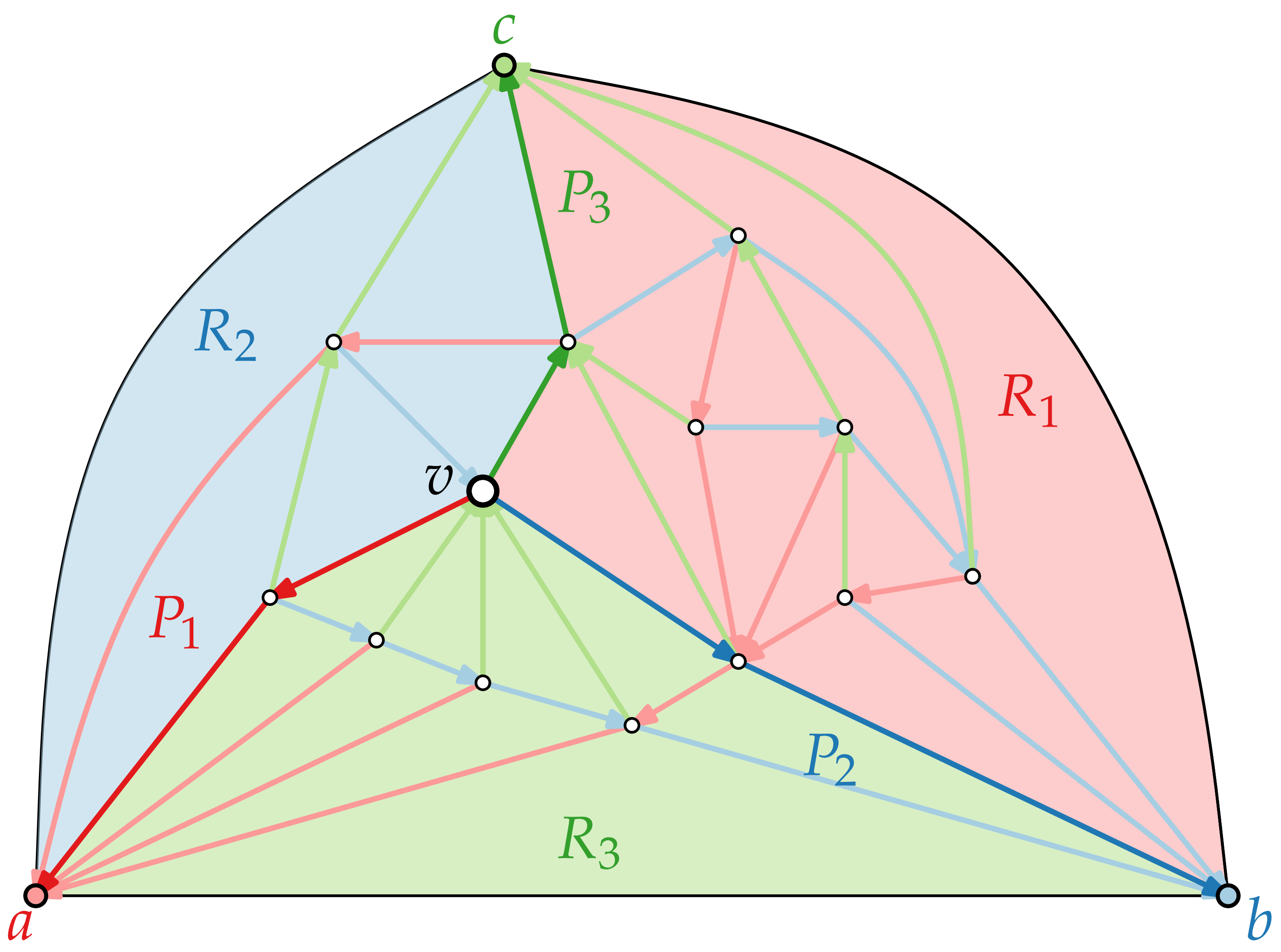

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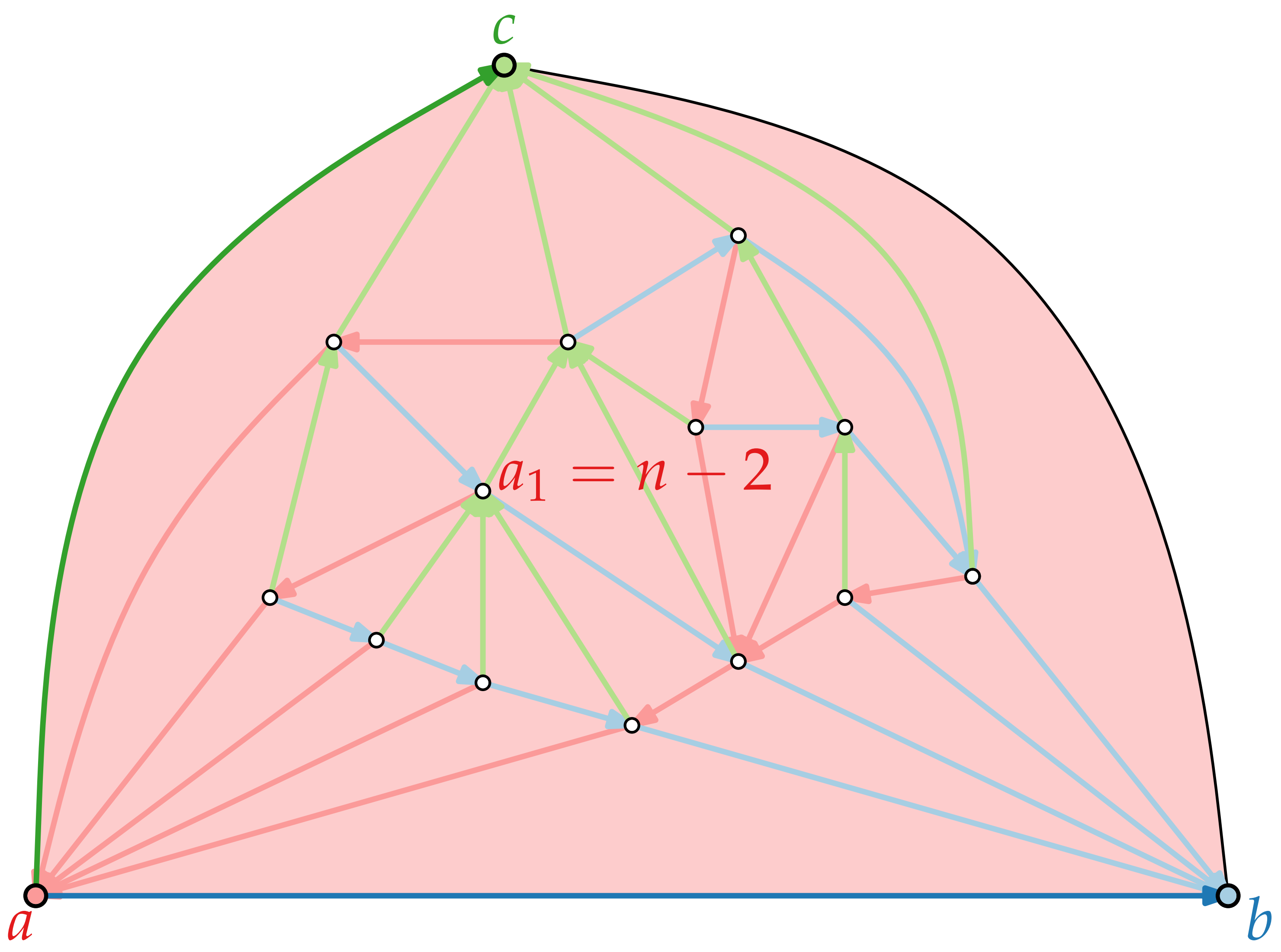

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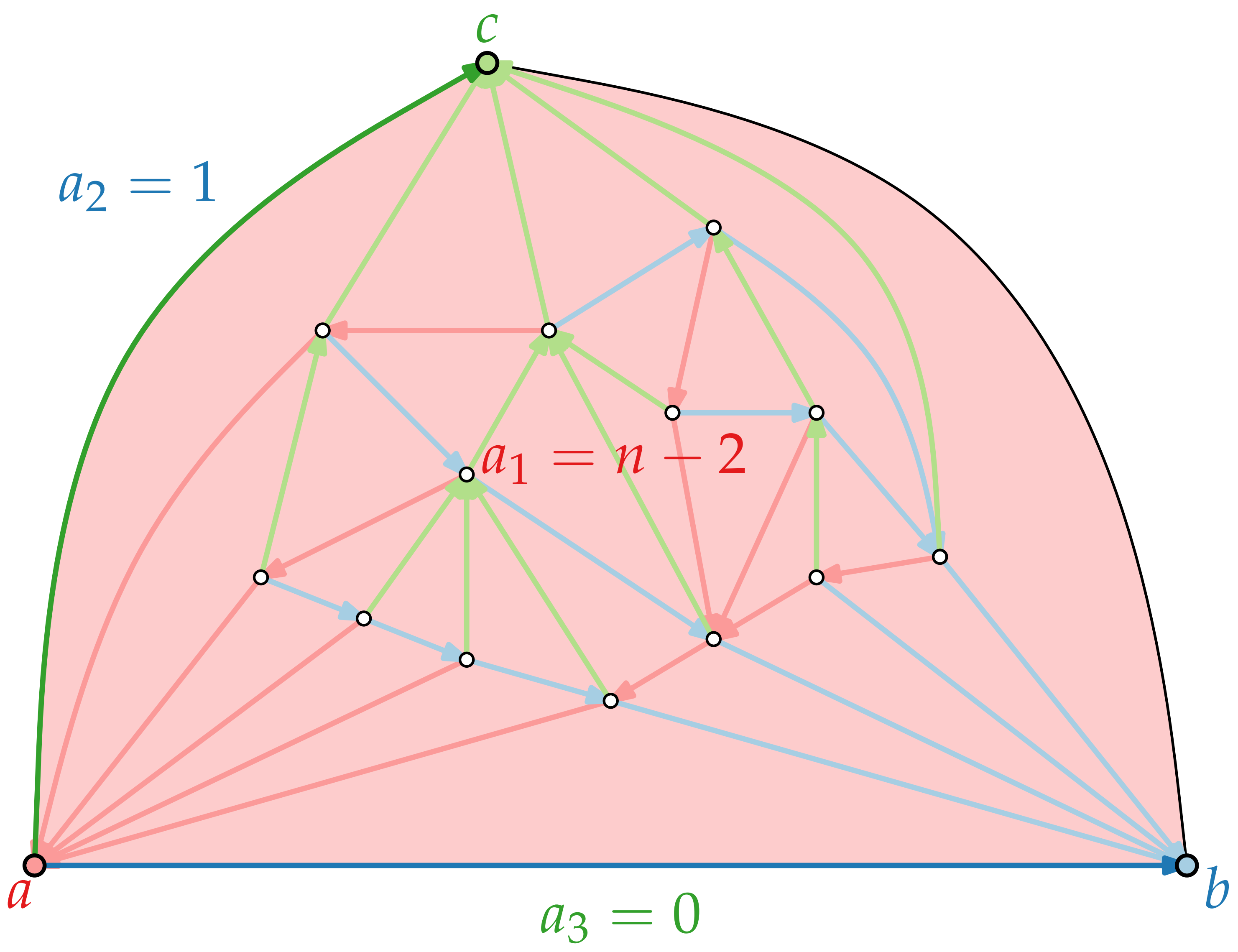

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- $v_1 + v_2 + v_3 = n - 1$

Schnyder Drawing*

Set $A = (0,0)$, $B = (n-1,0)$, and $C = (0,n-1)$.

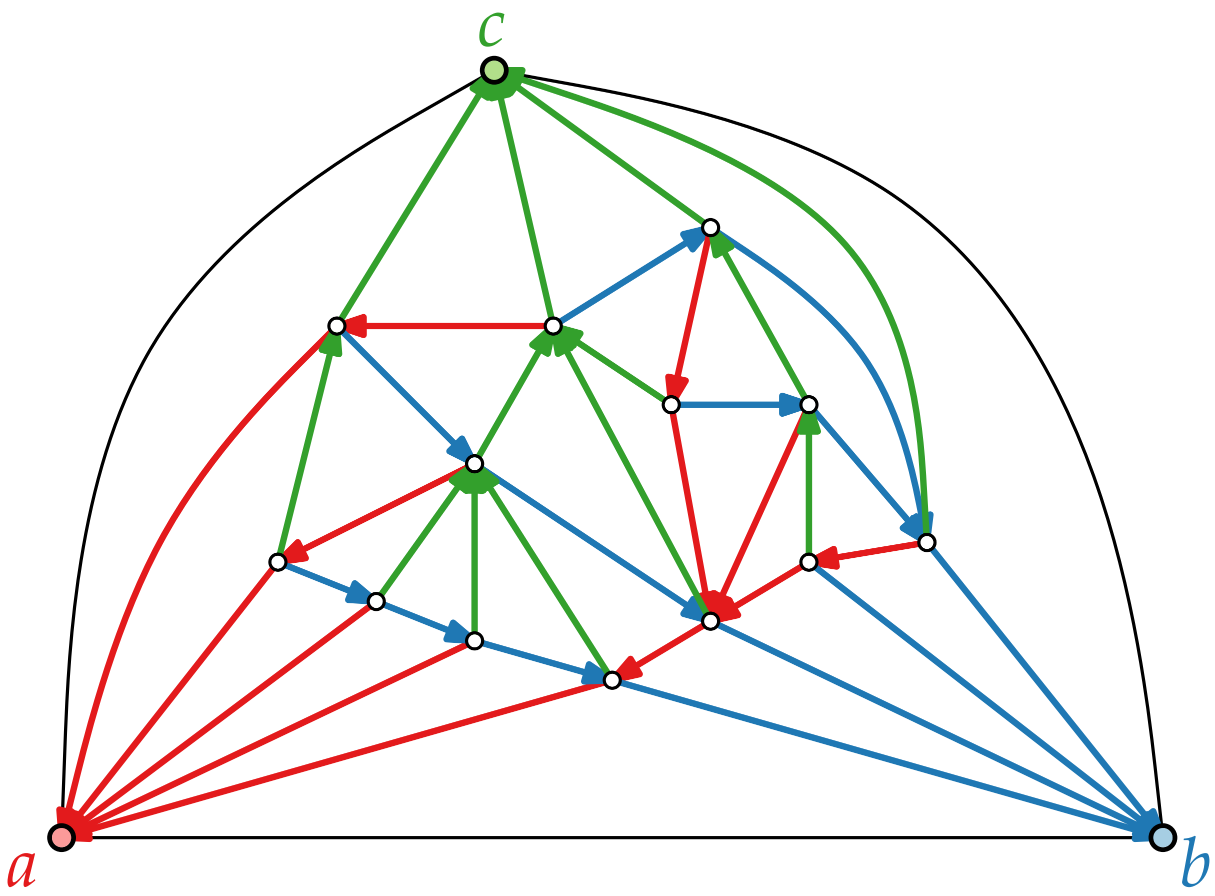
Theorem. [Schnyder '90]

For a plane triangulation G, the mapping

$$f : v \mapsto \frac{1}{n-1}(v_1, v_2, v_3)$$

is a barycentric representation of G, which thus gives a planar straight-line drawing of G on the $(n-2) \times (n-2)$ grid.

Schnyder Drawing* – Example



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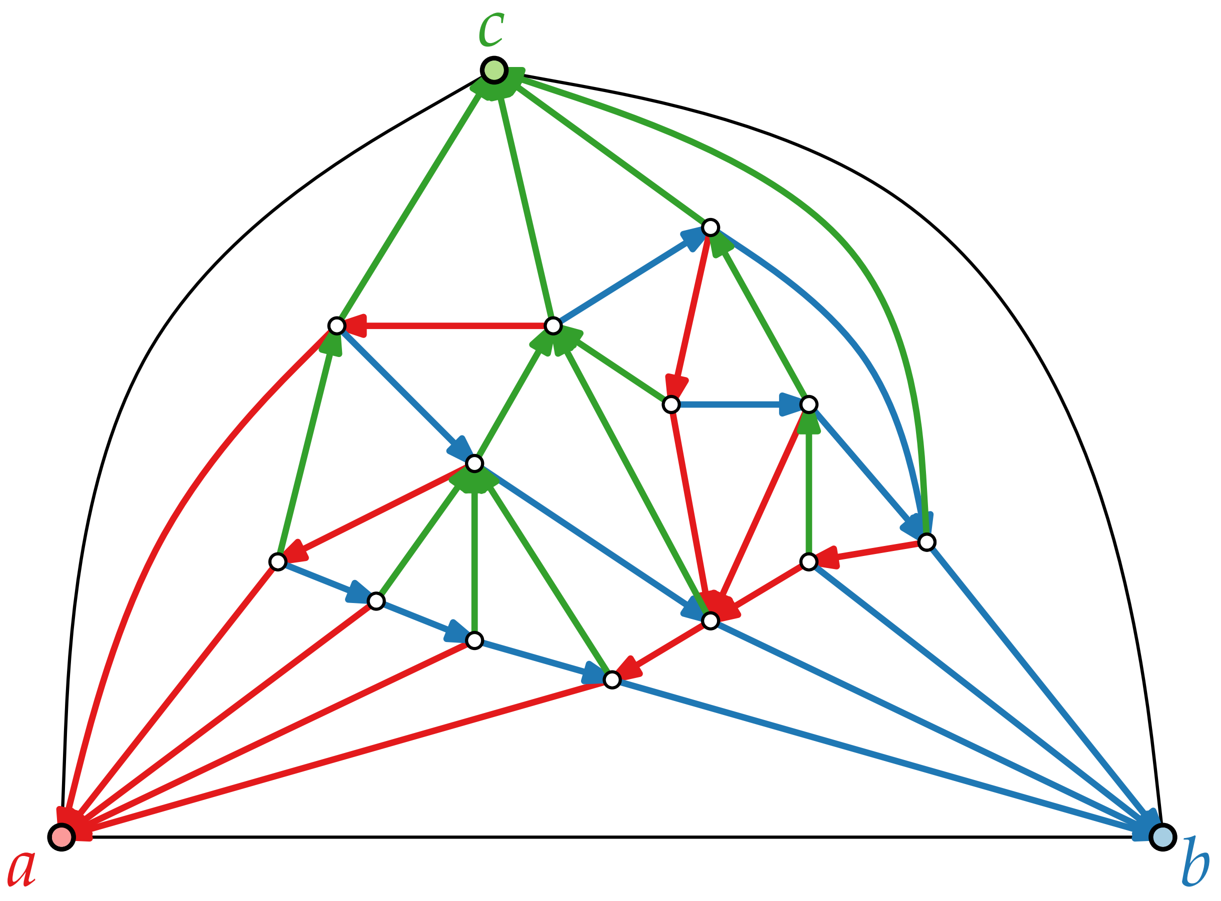
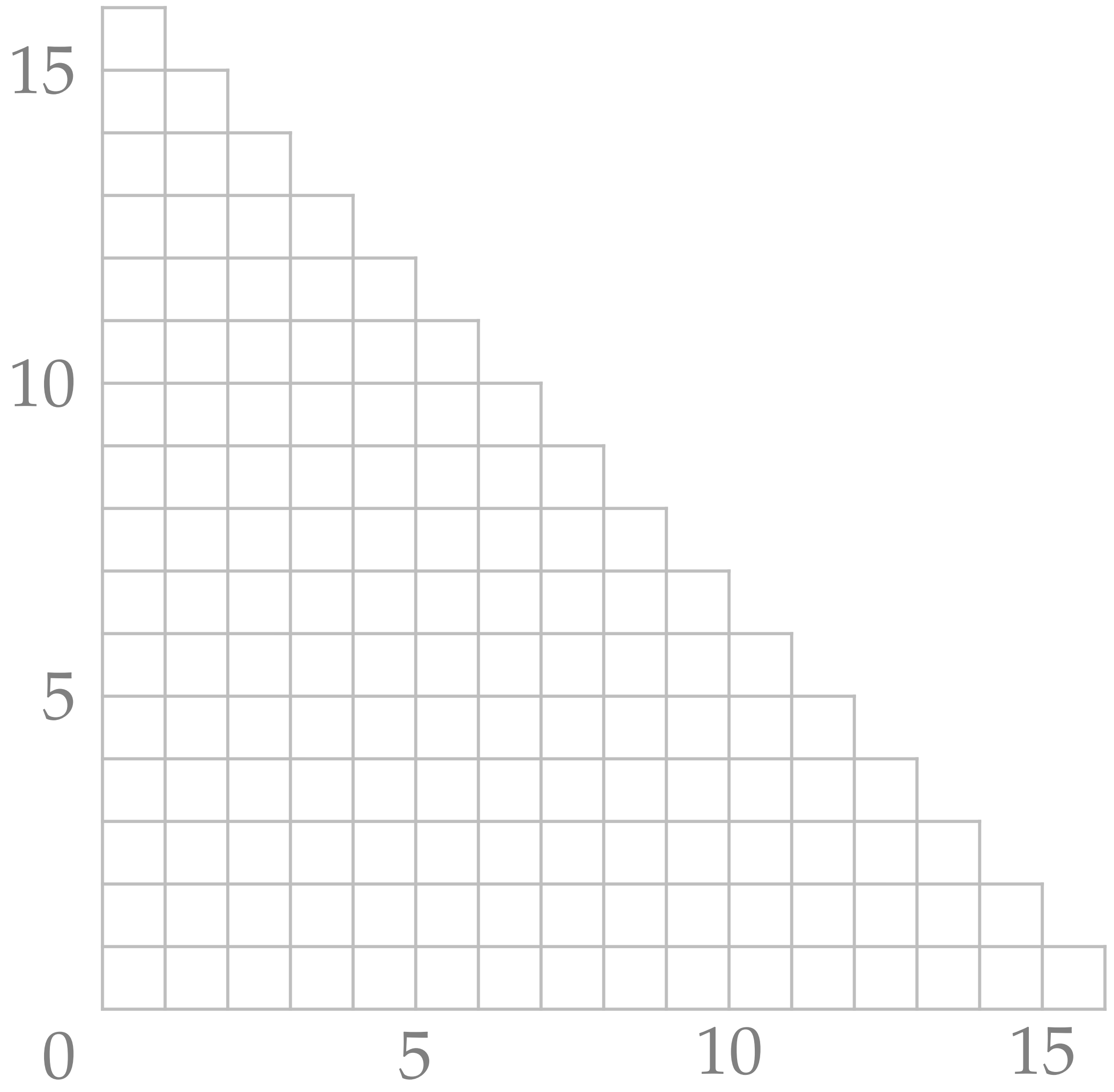
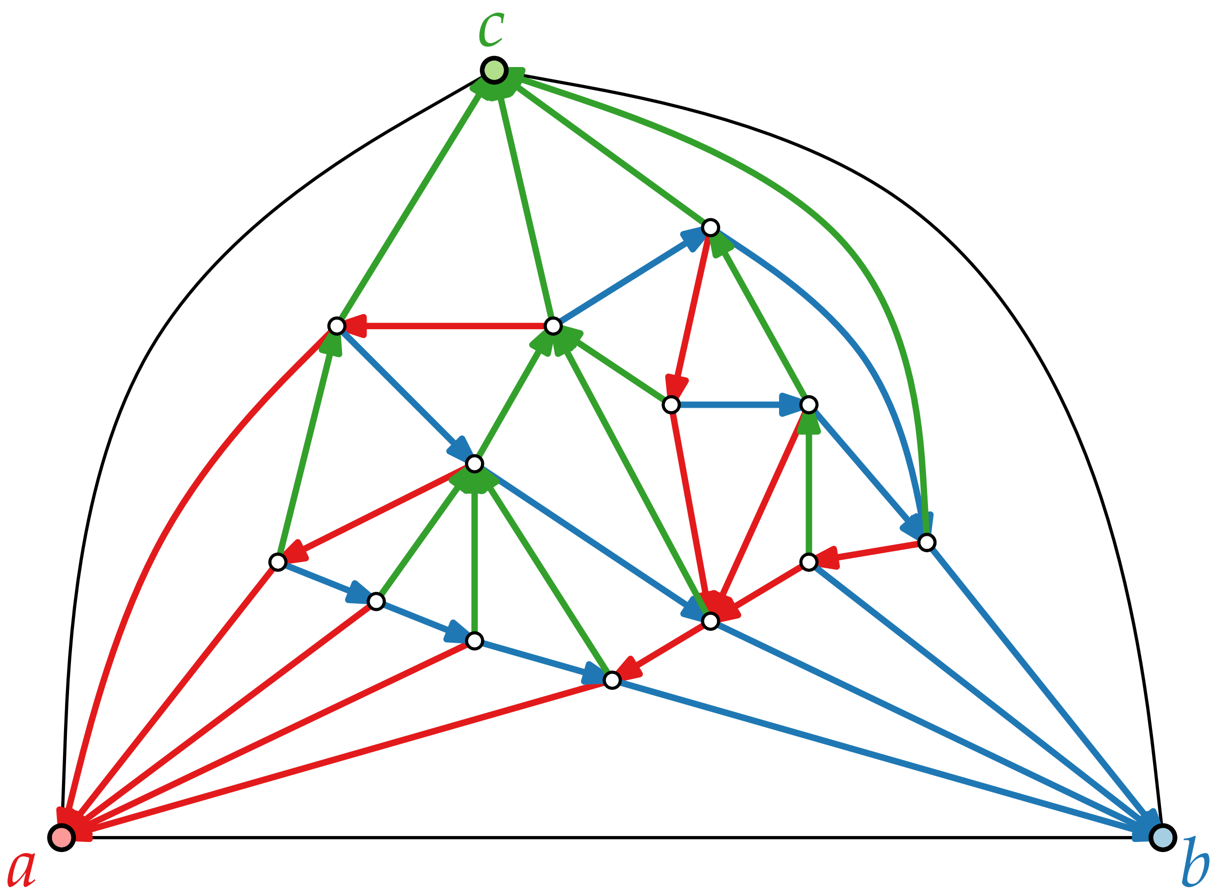


$n = 16, n - 2 = 14$

Schnyder Drawing* – Example





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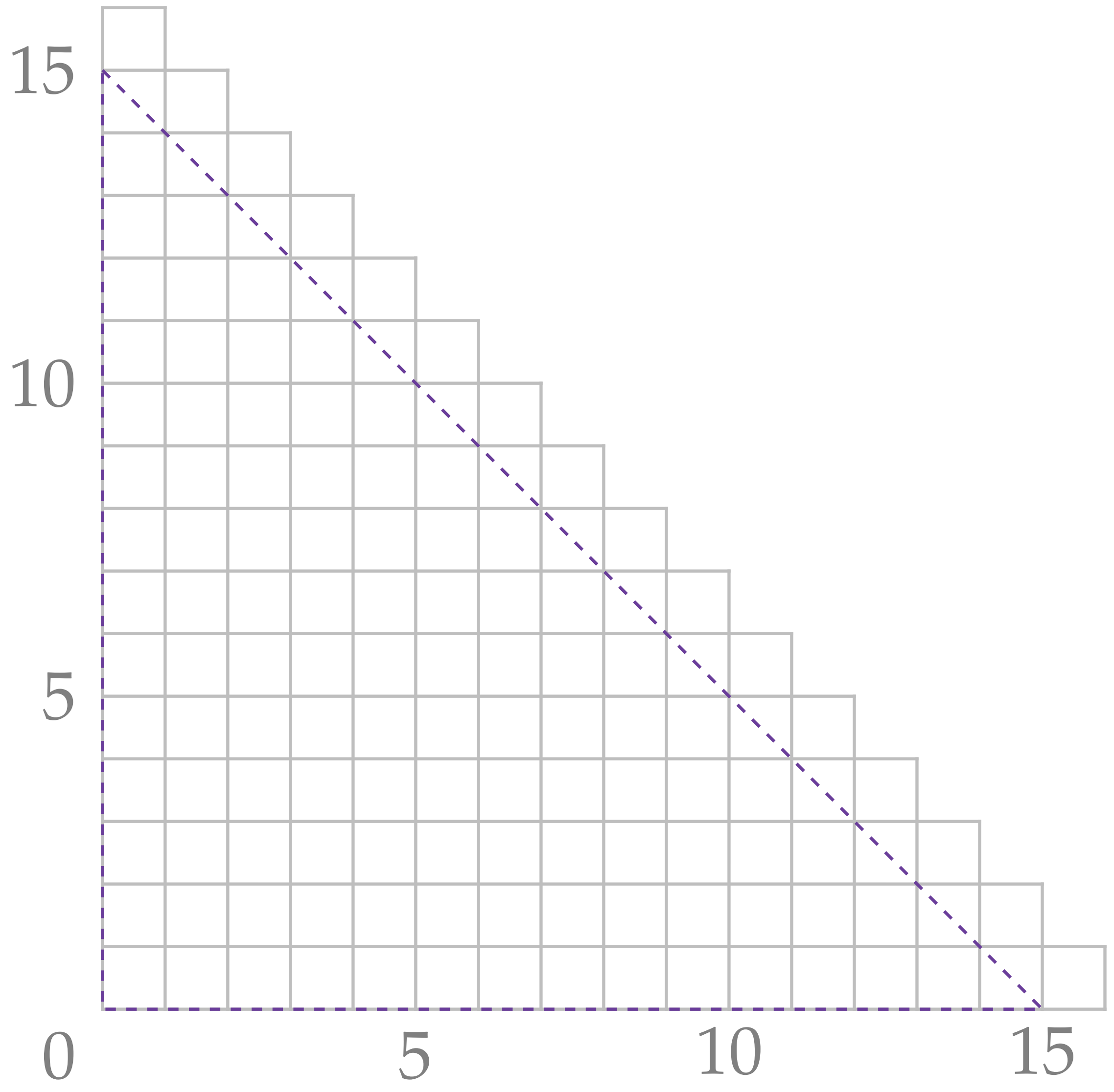

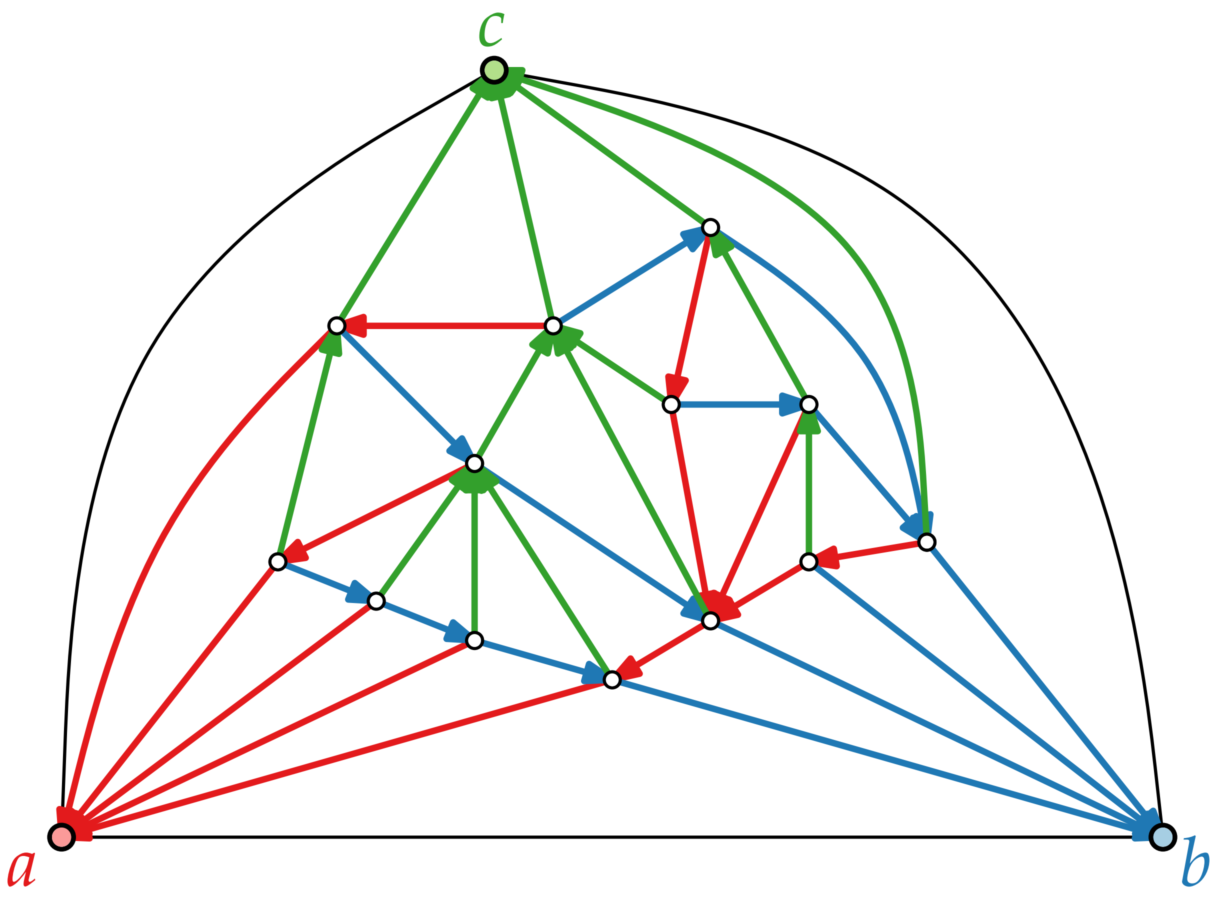

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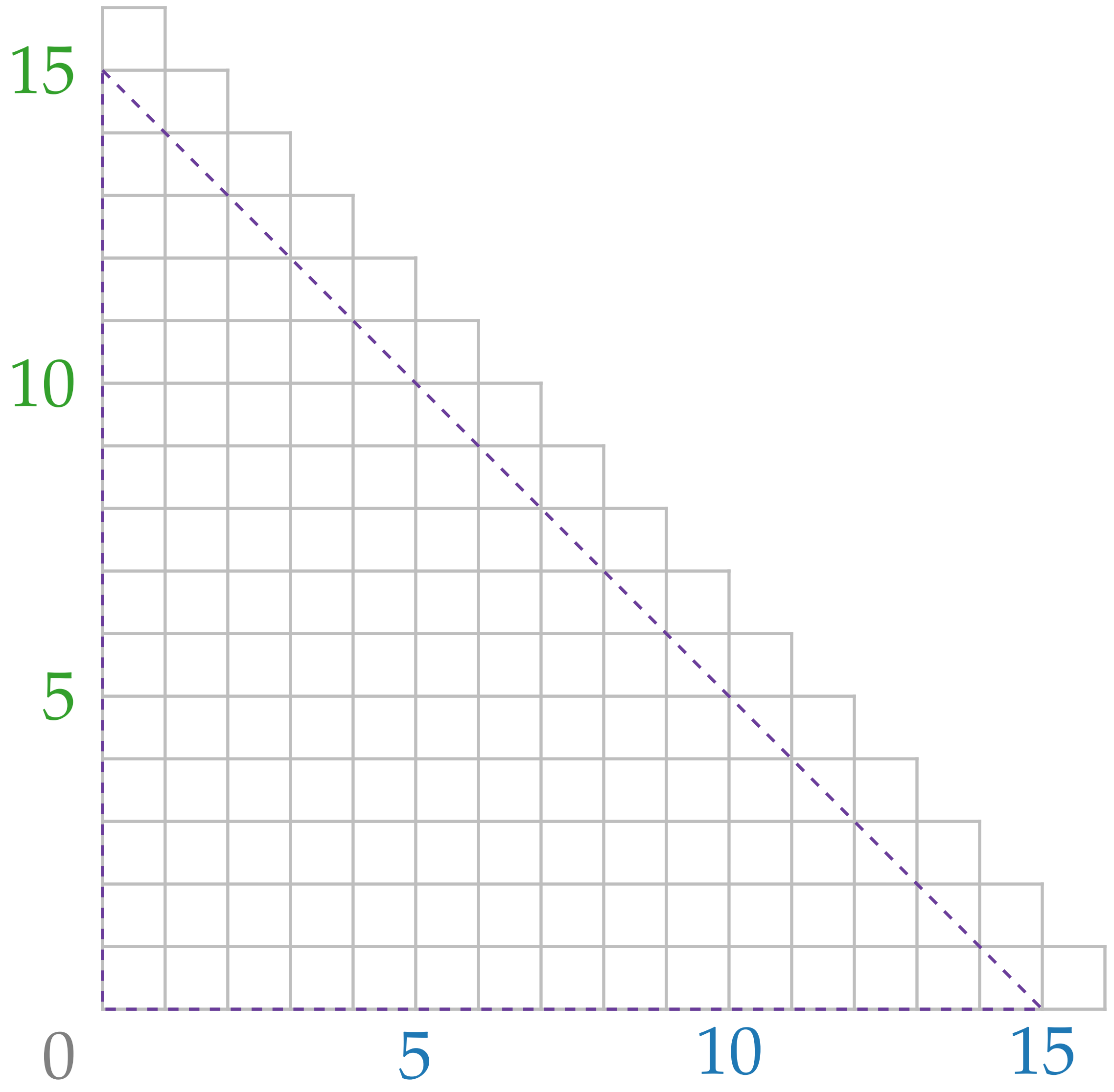

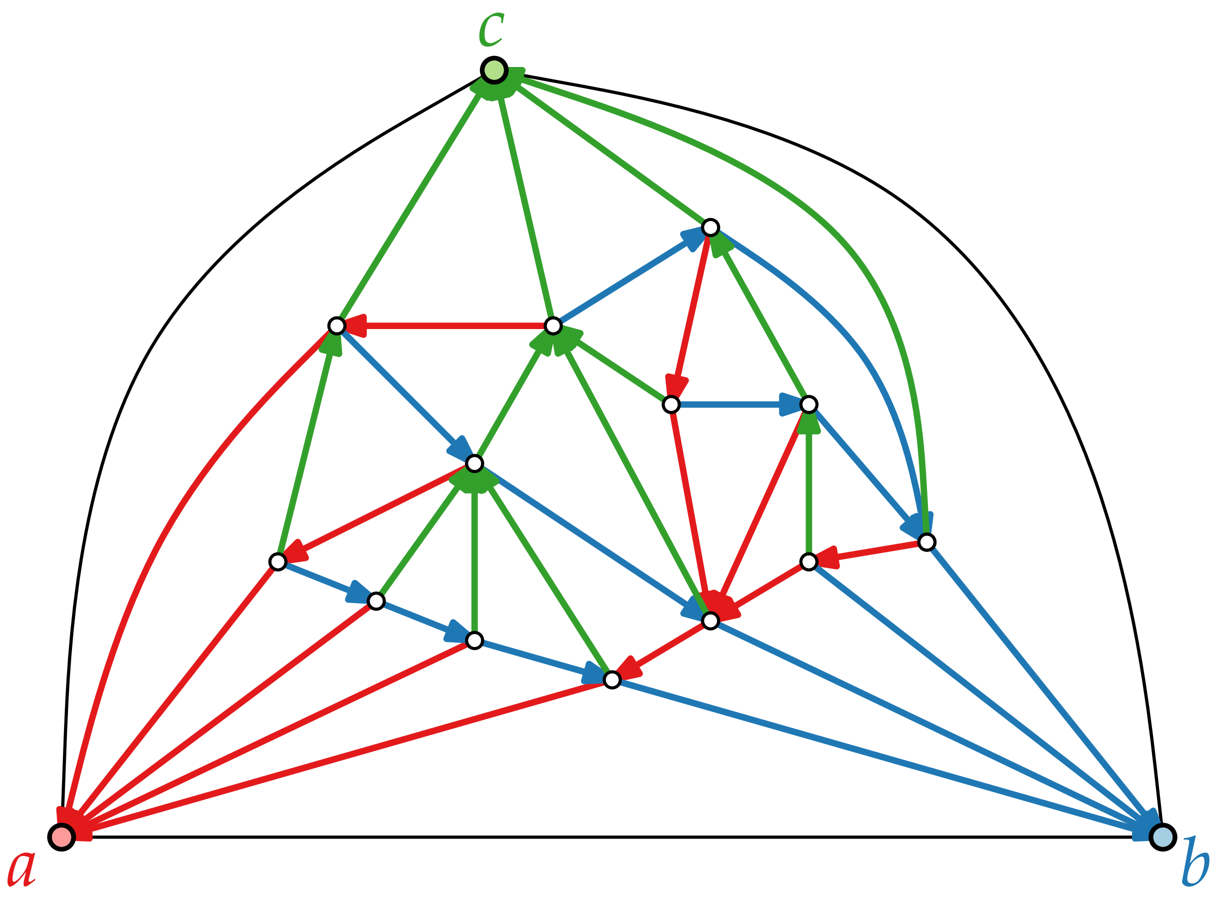

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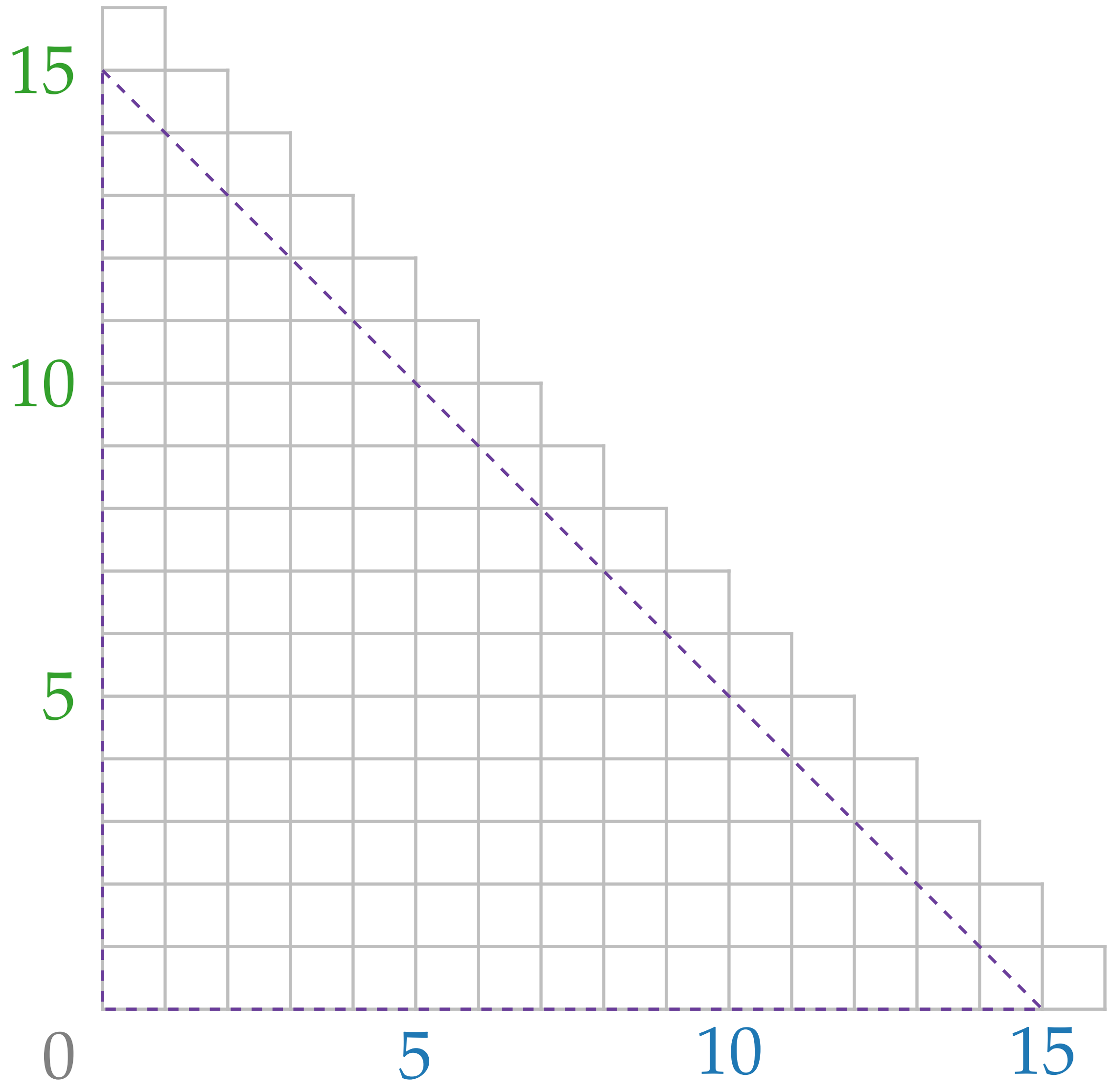
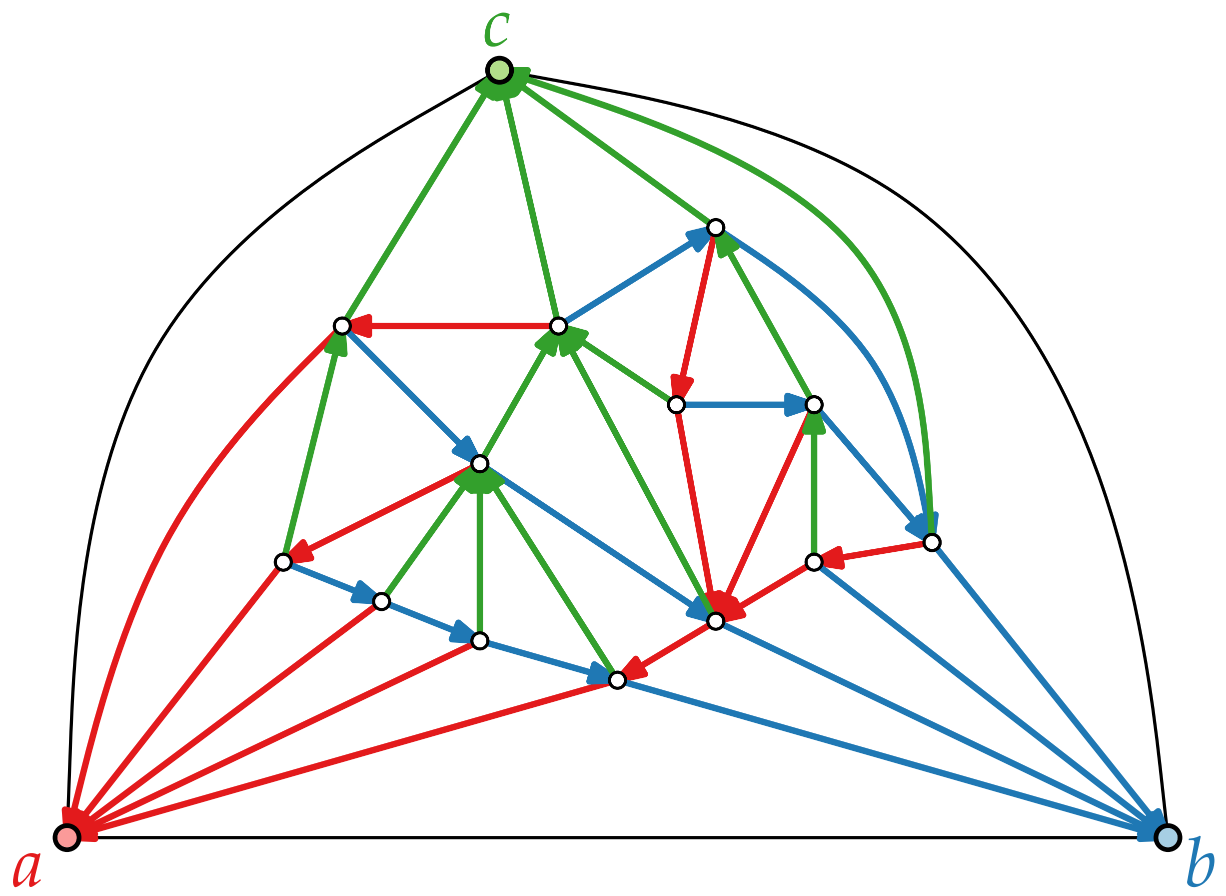
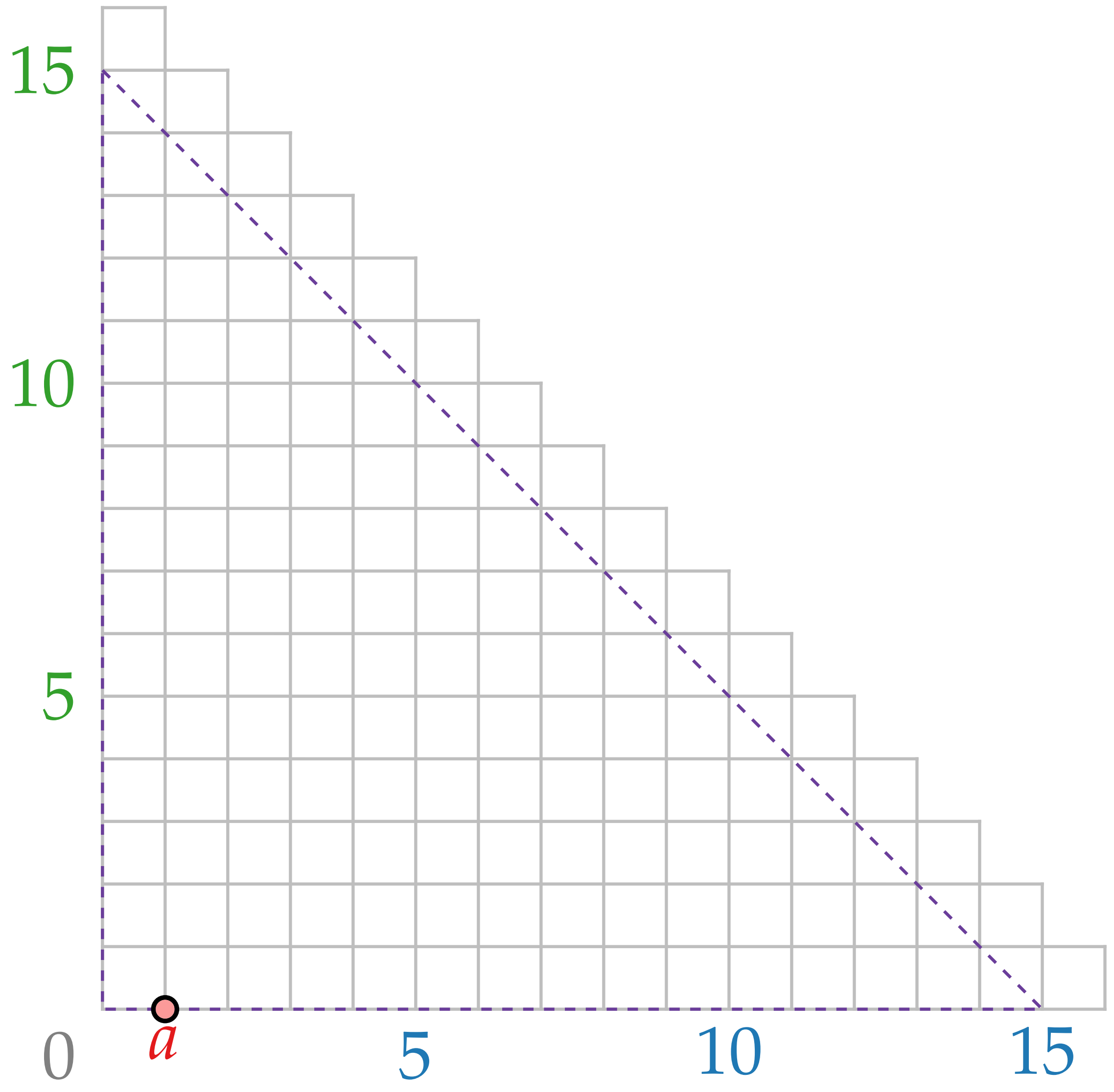


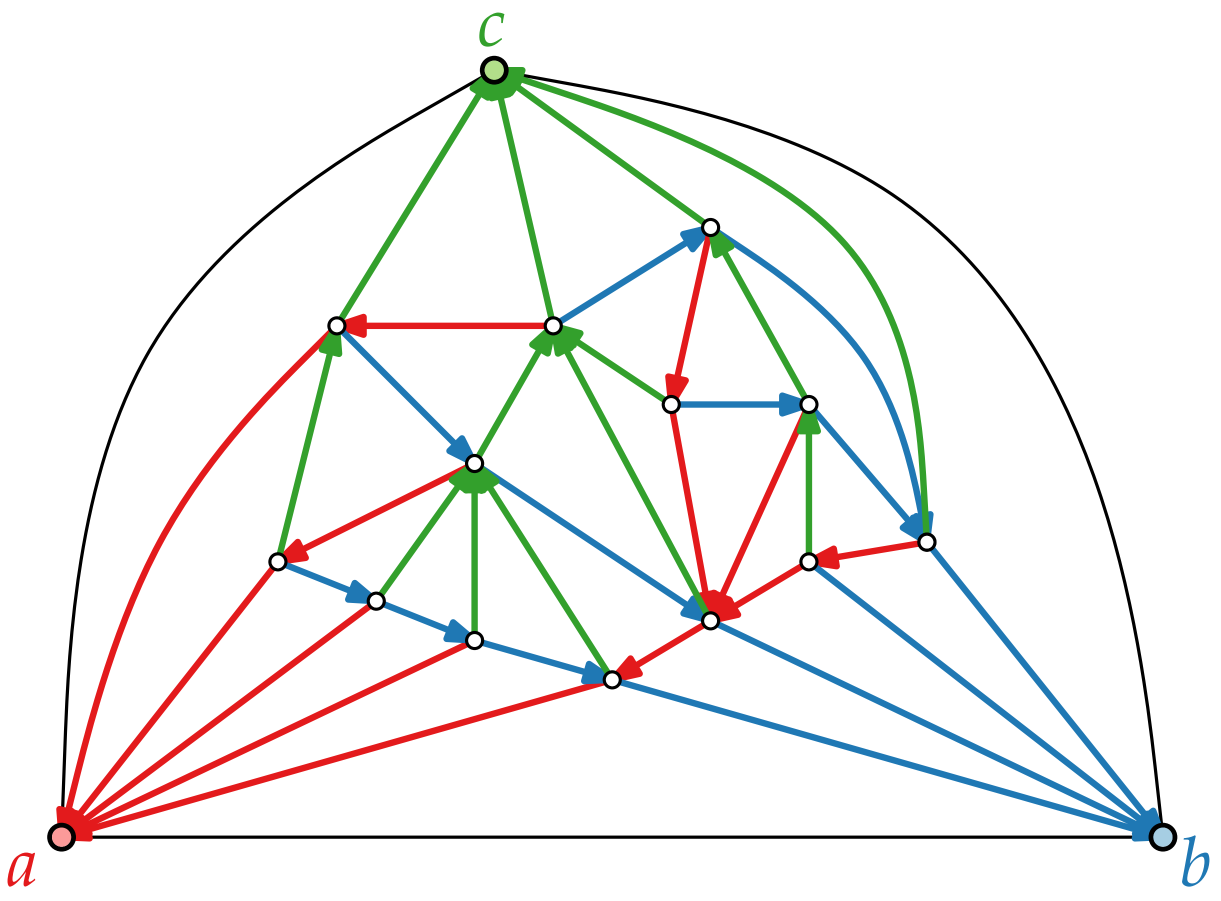


$n = 16, n - 2 = 14$

$f(a) = (n-2, 1, 0)$

Schnyder Drawing* – Example





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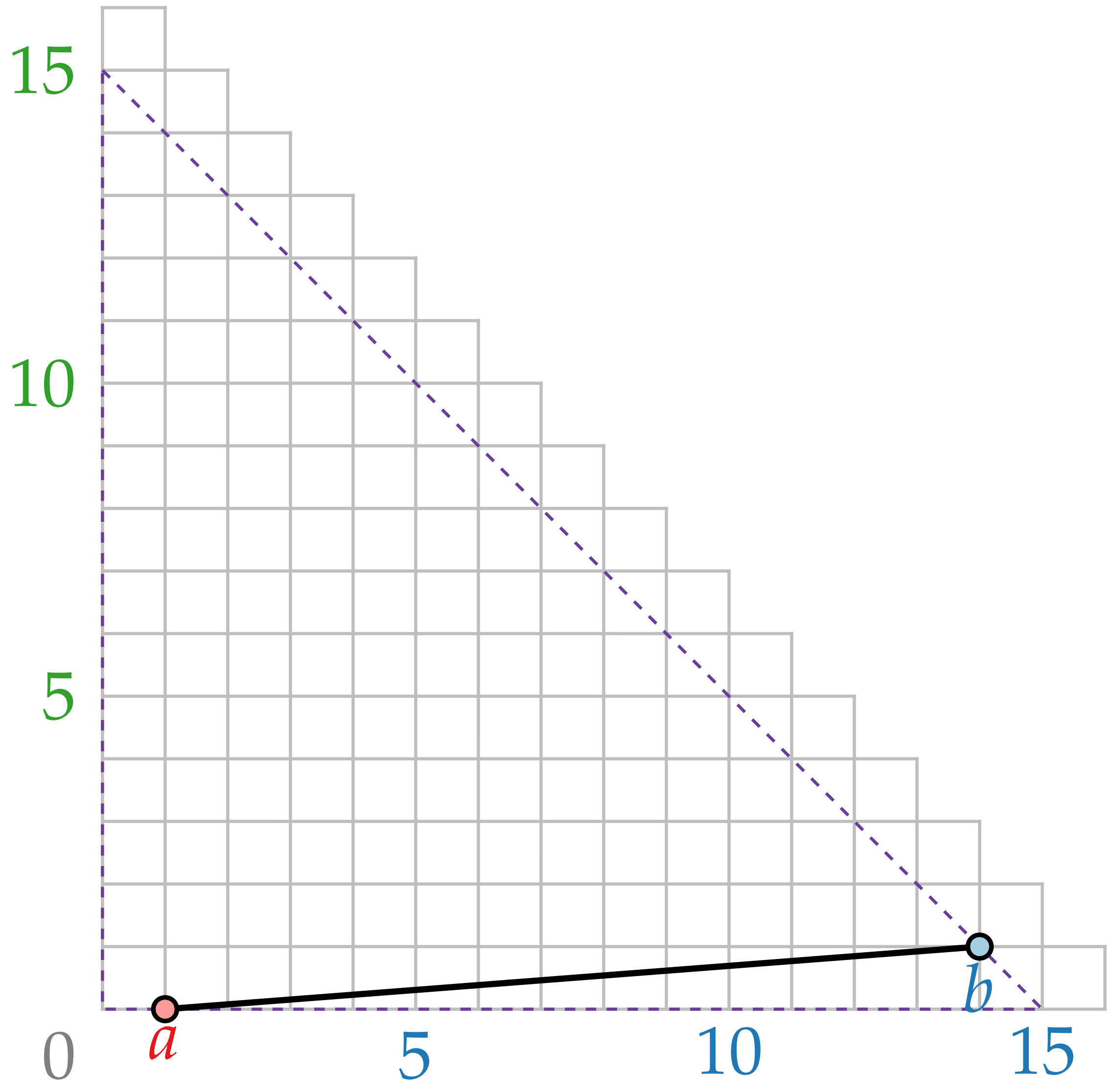
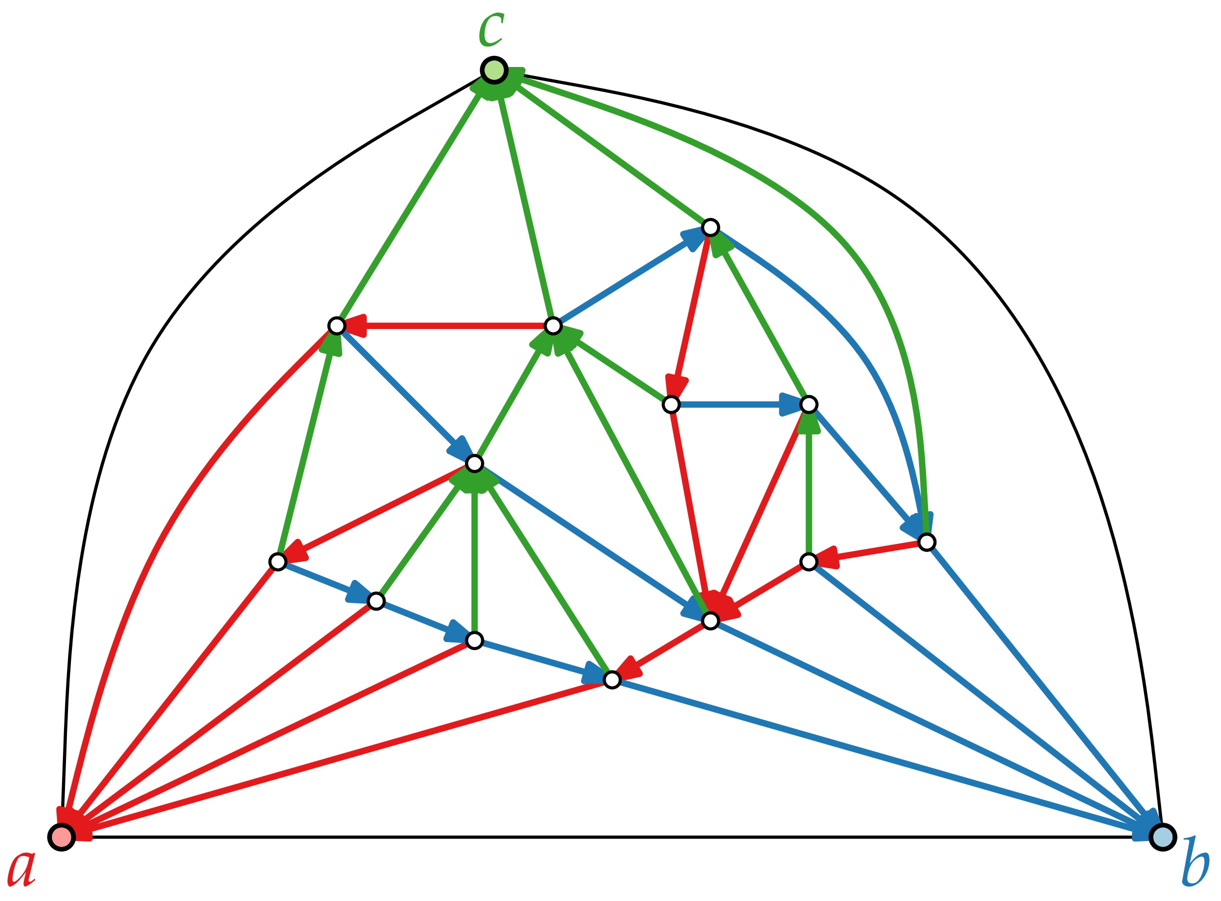


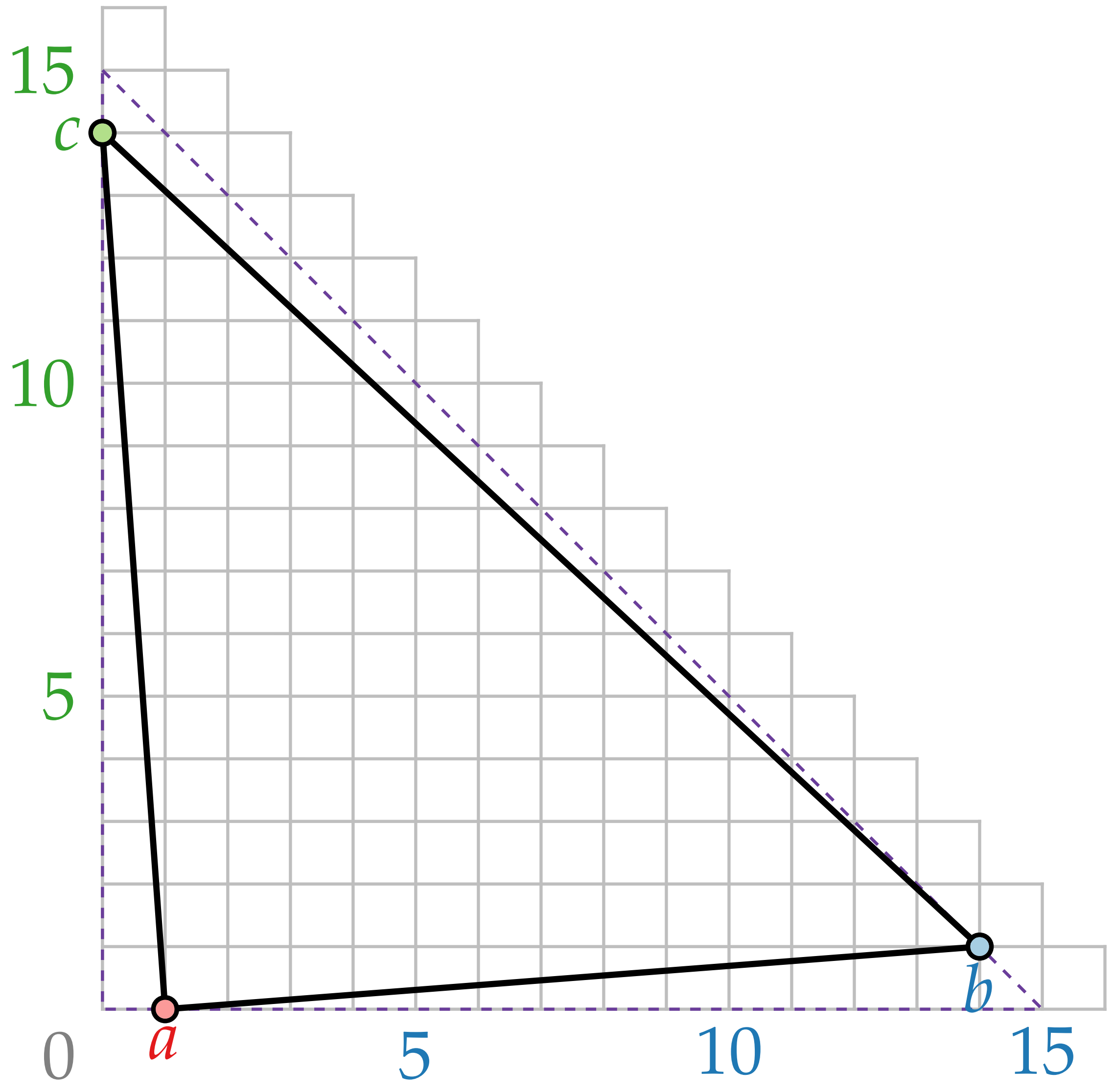


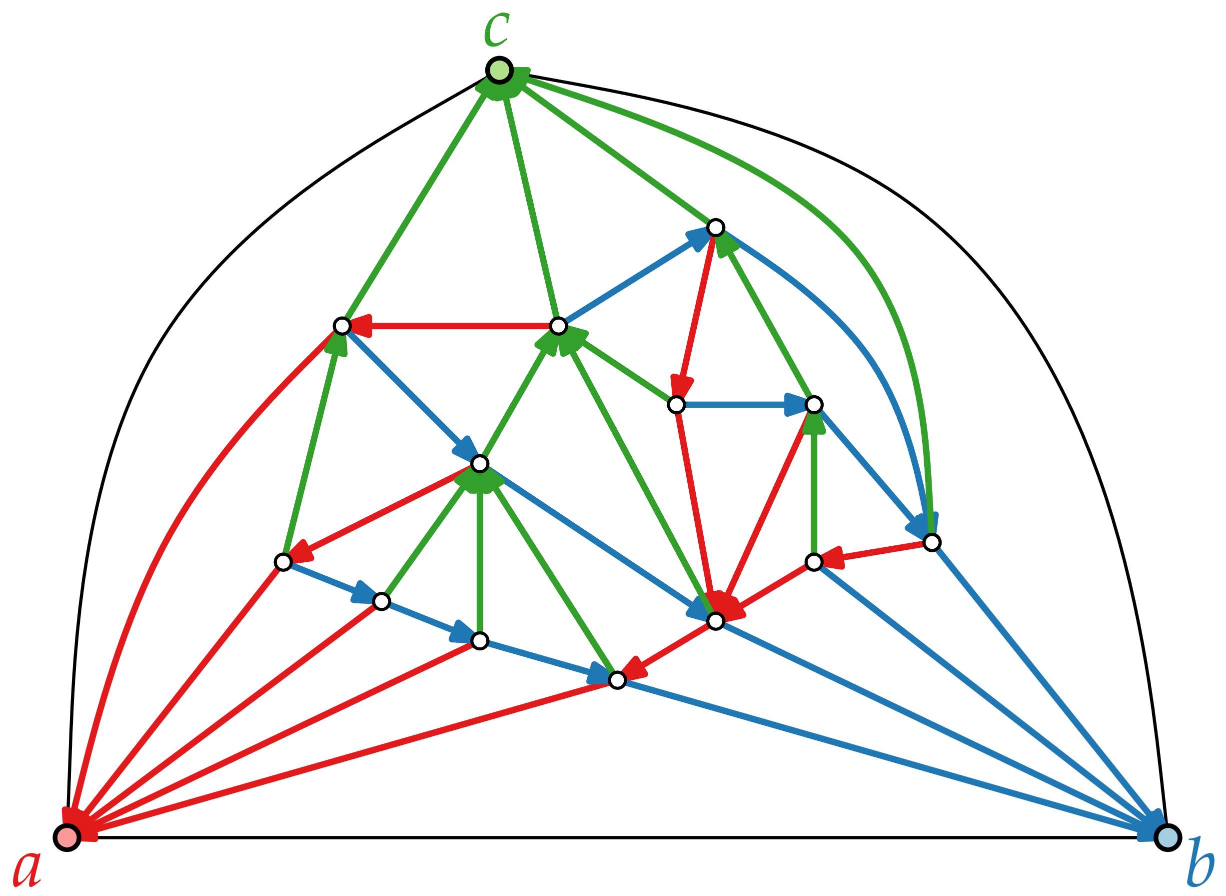
$n = 16, n - 2 = 14$

$f(a) = (n - 2, 1, 0)$

$f(b) = (0, n - 2, 1)$

Schnyder Drawing* – Example





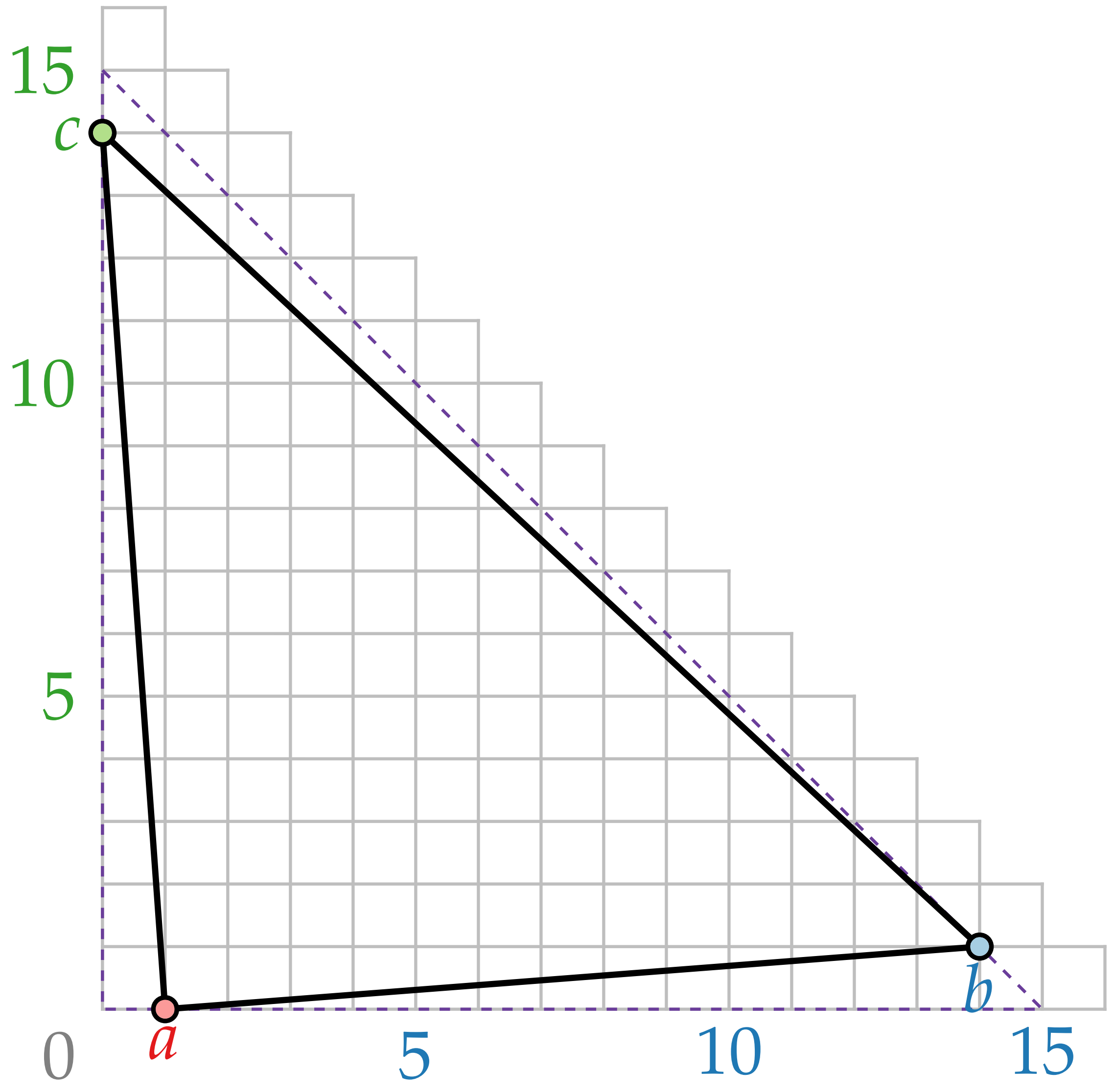
$n = 16, n - 2 = 14$

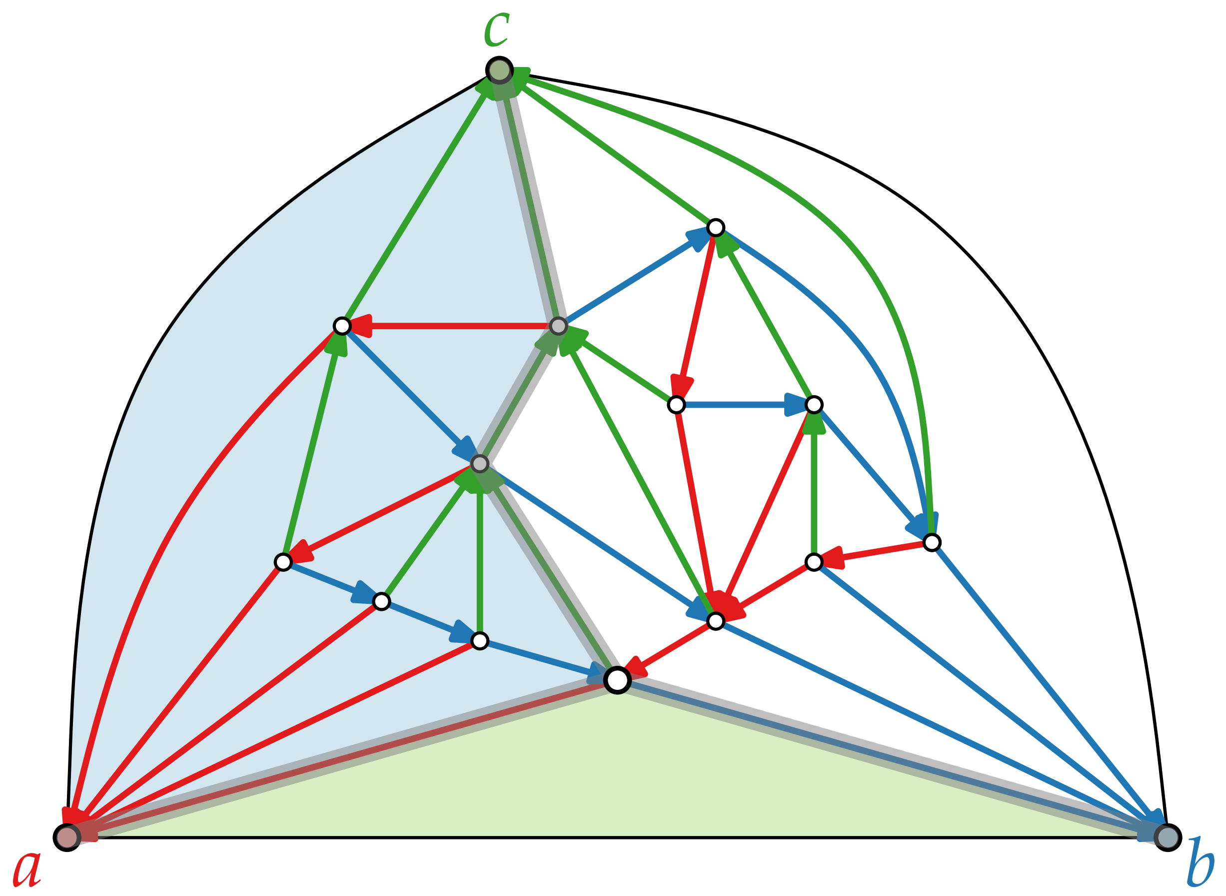
$f(a) = (n-2, 1, 0)$

$f(b) = (0, n-2, 1)$

$f(c) = (1, 0, n-2)$

Schnyder Drawing* – Example





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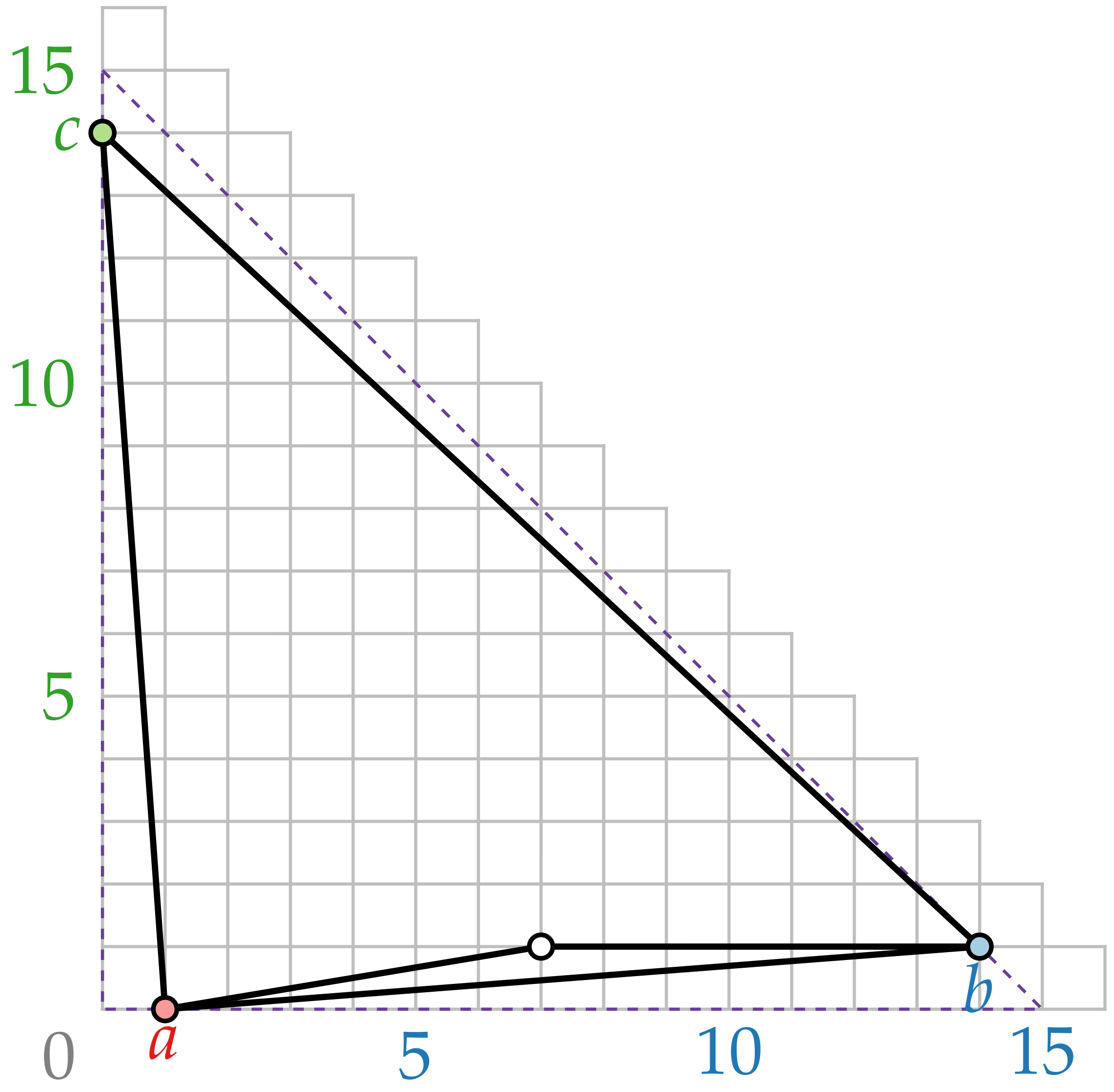
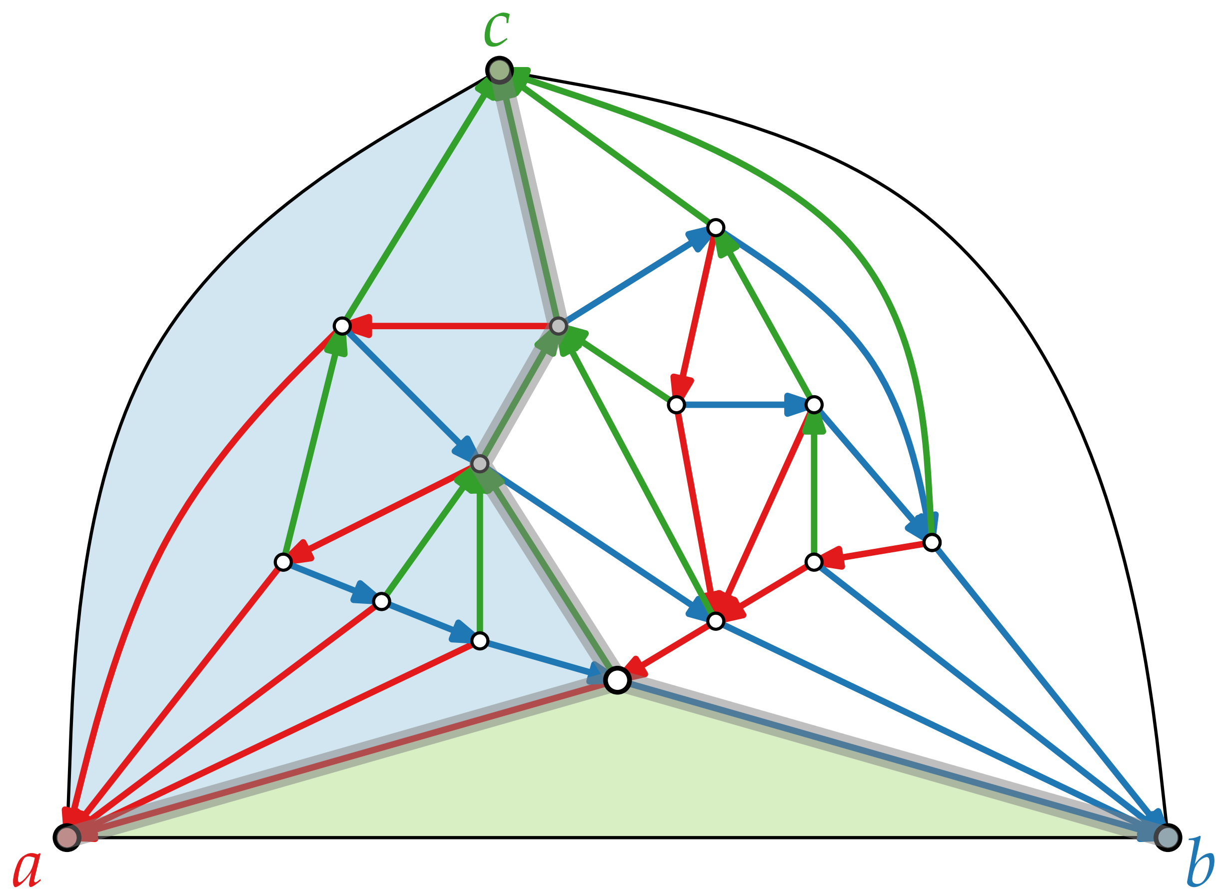
Schnyder Drawing⋆ – Example





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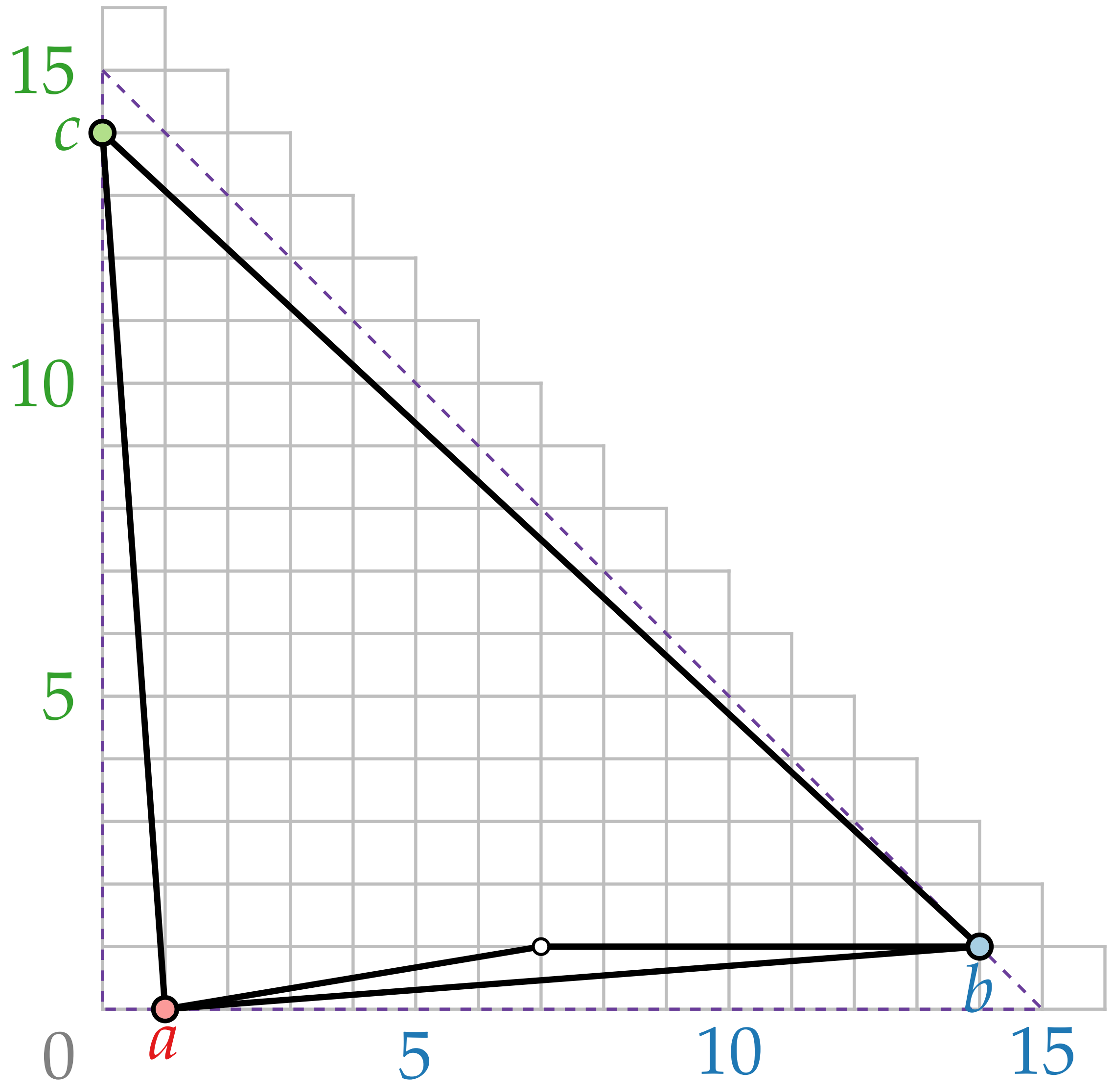

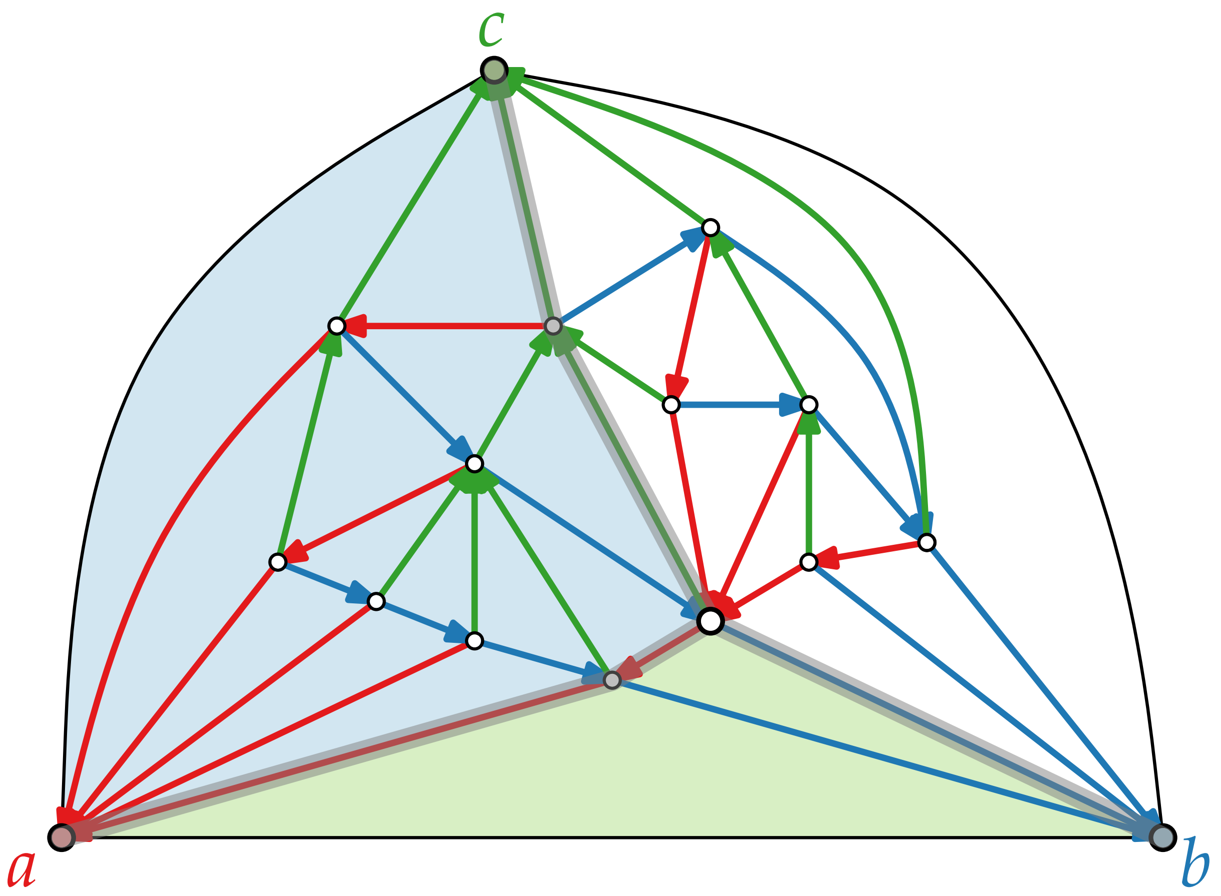

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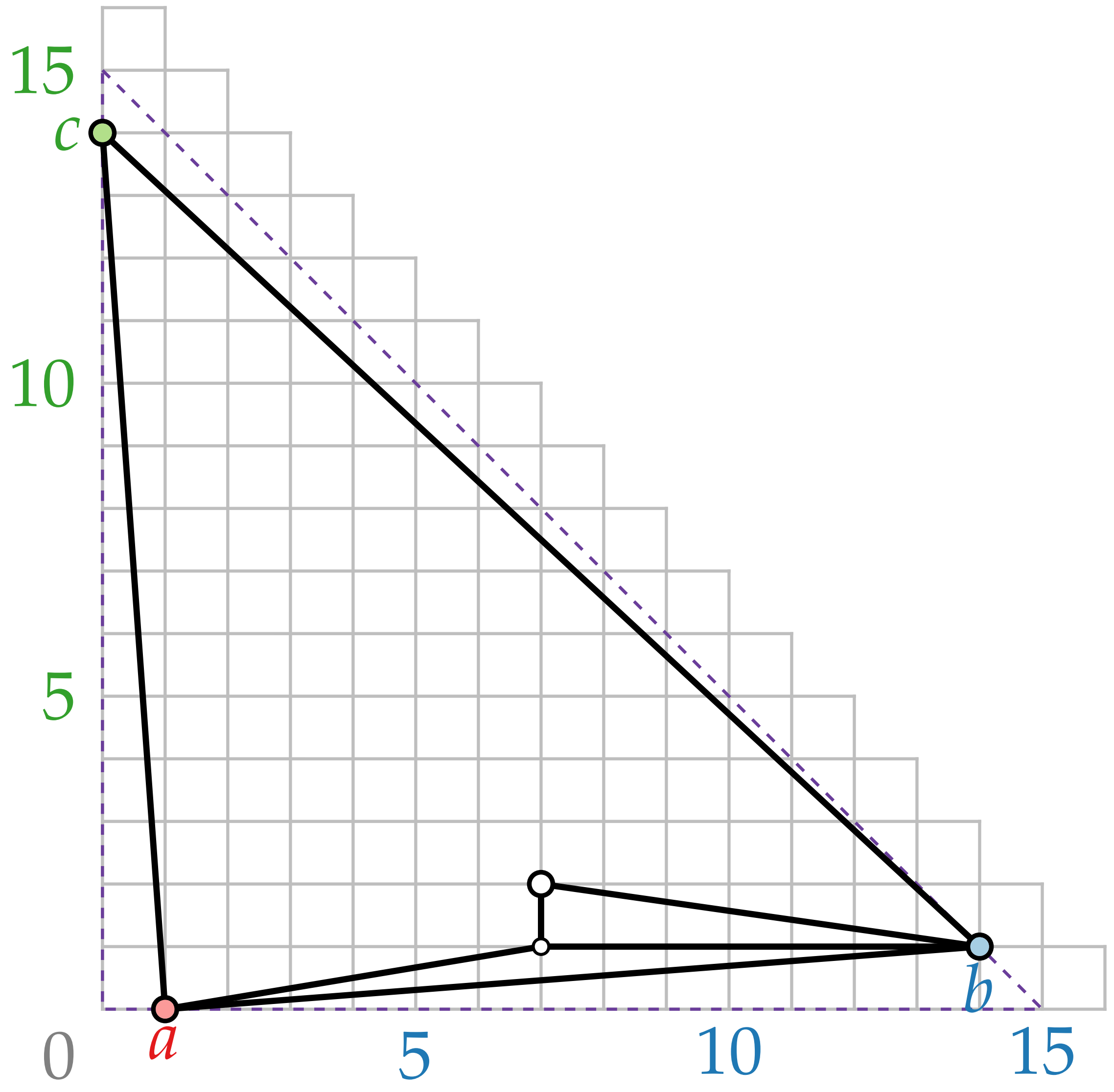

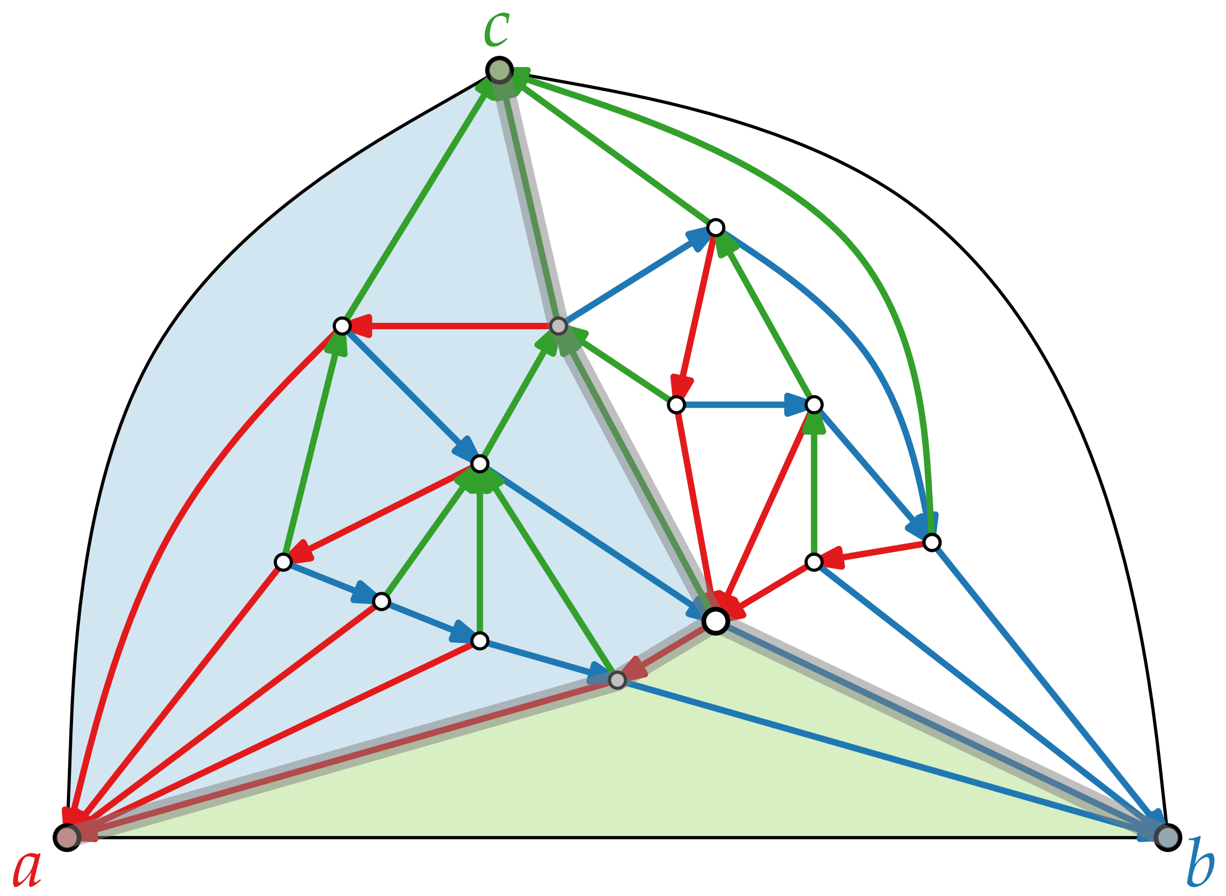

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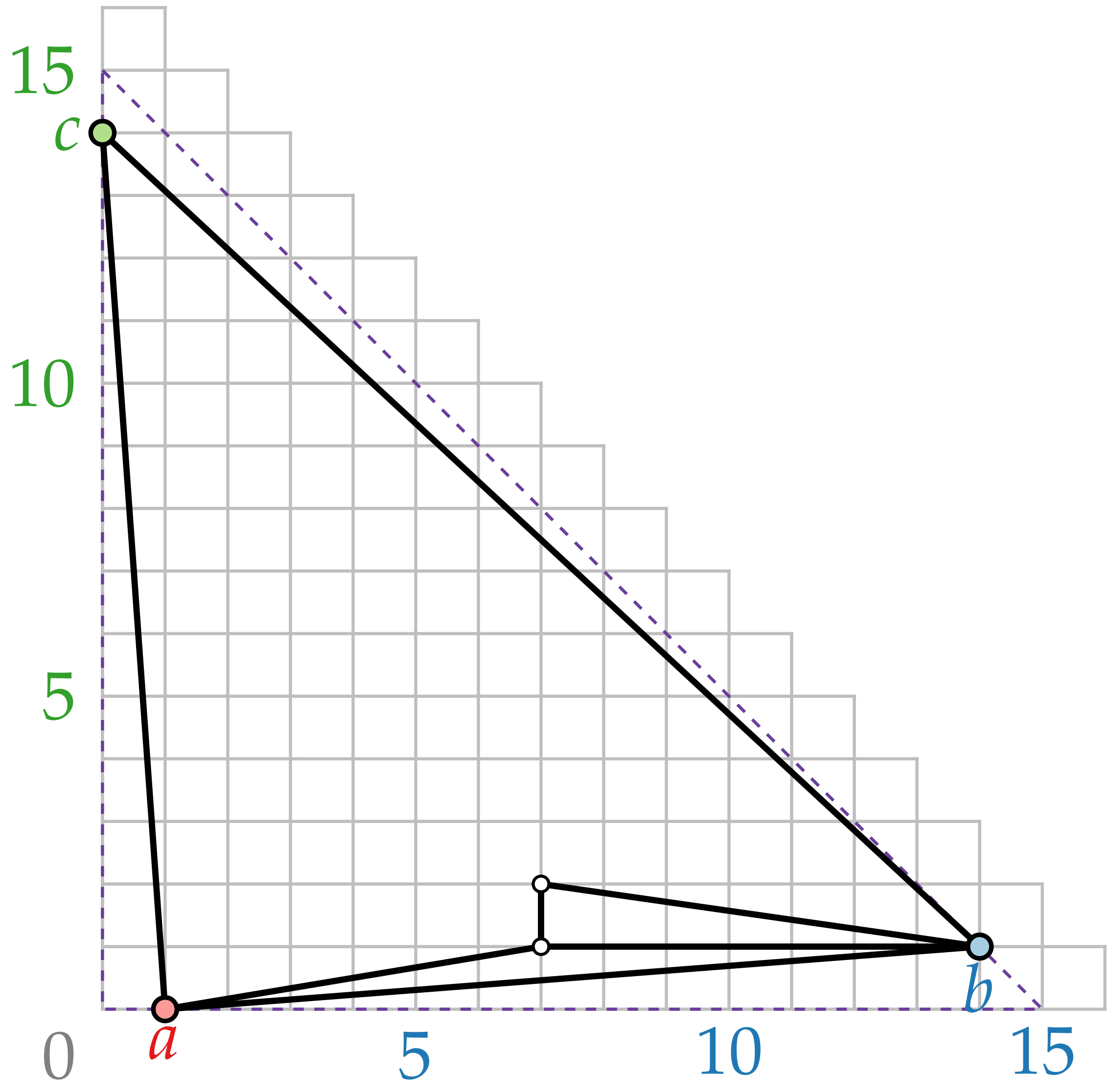

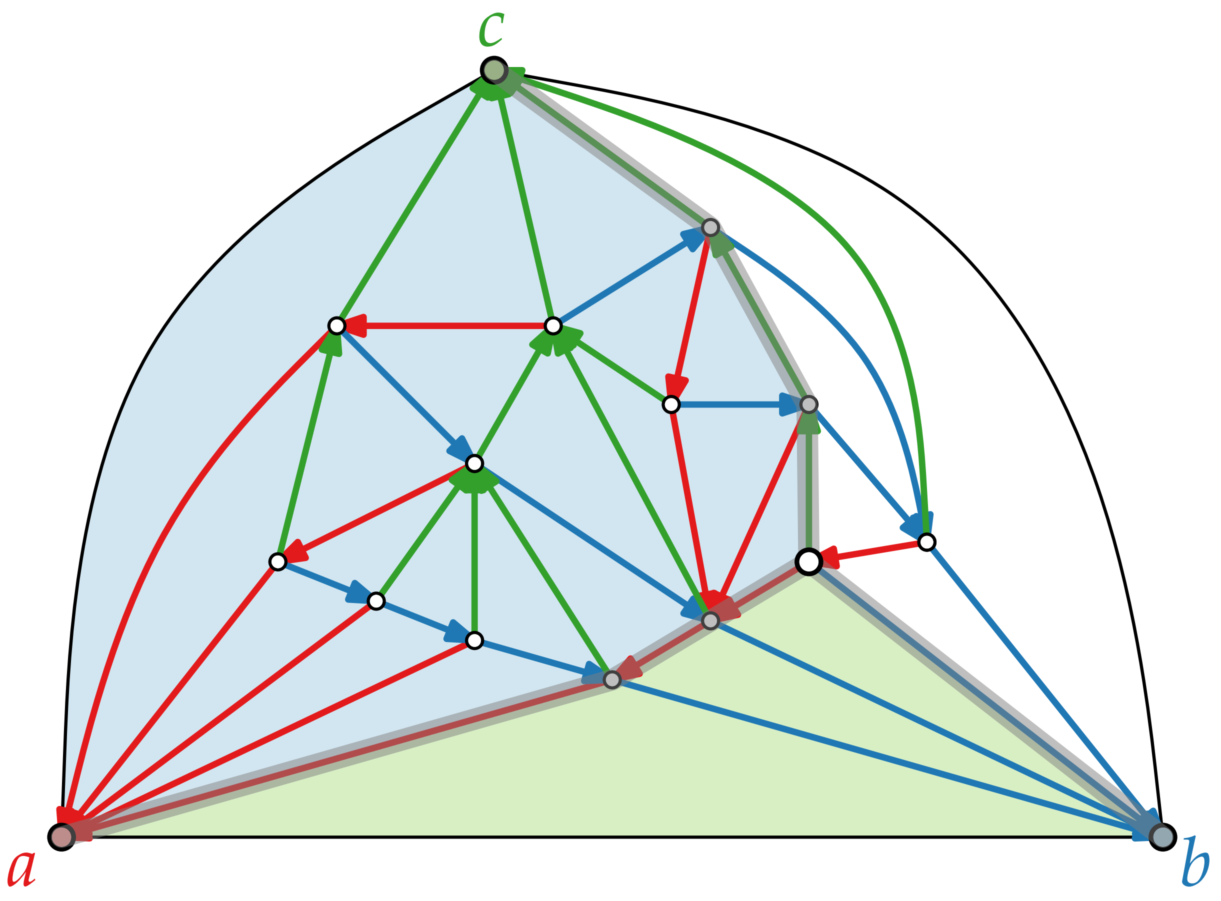

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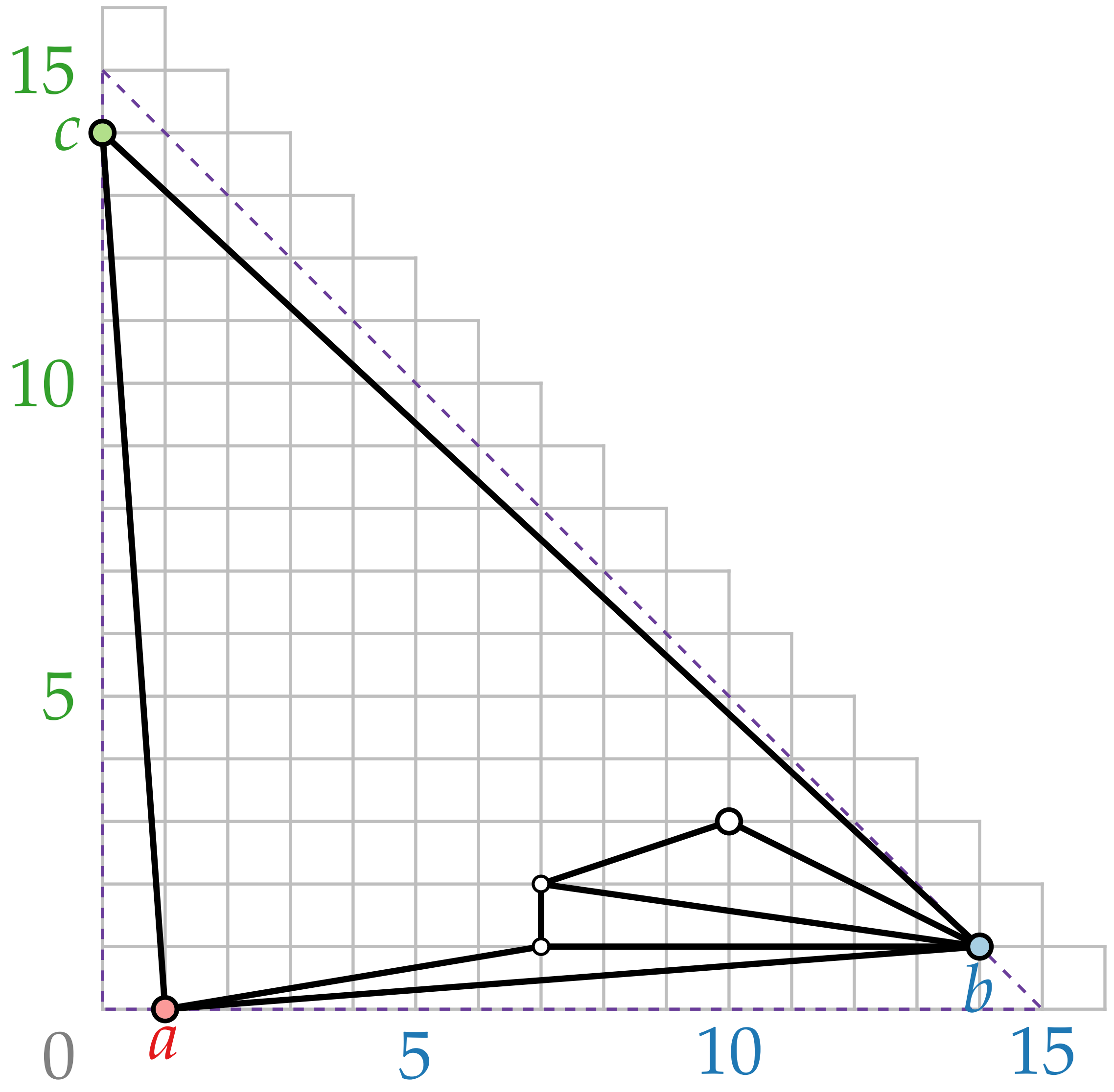

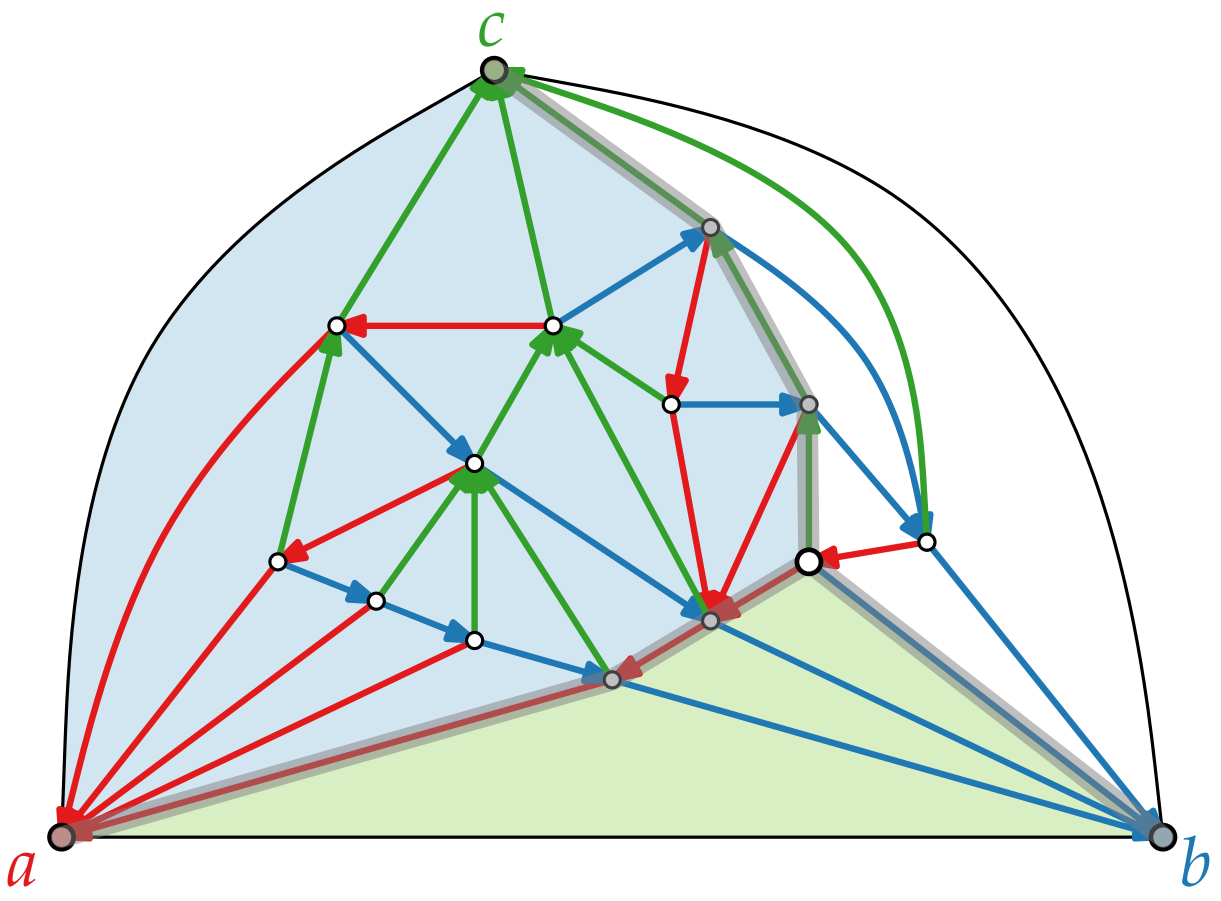

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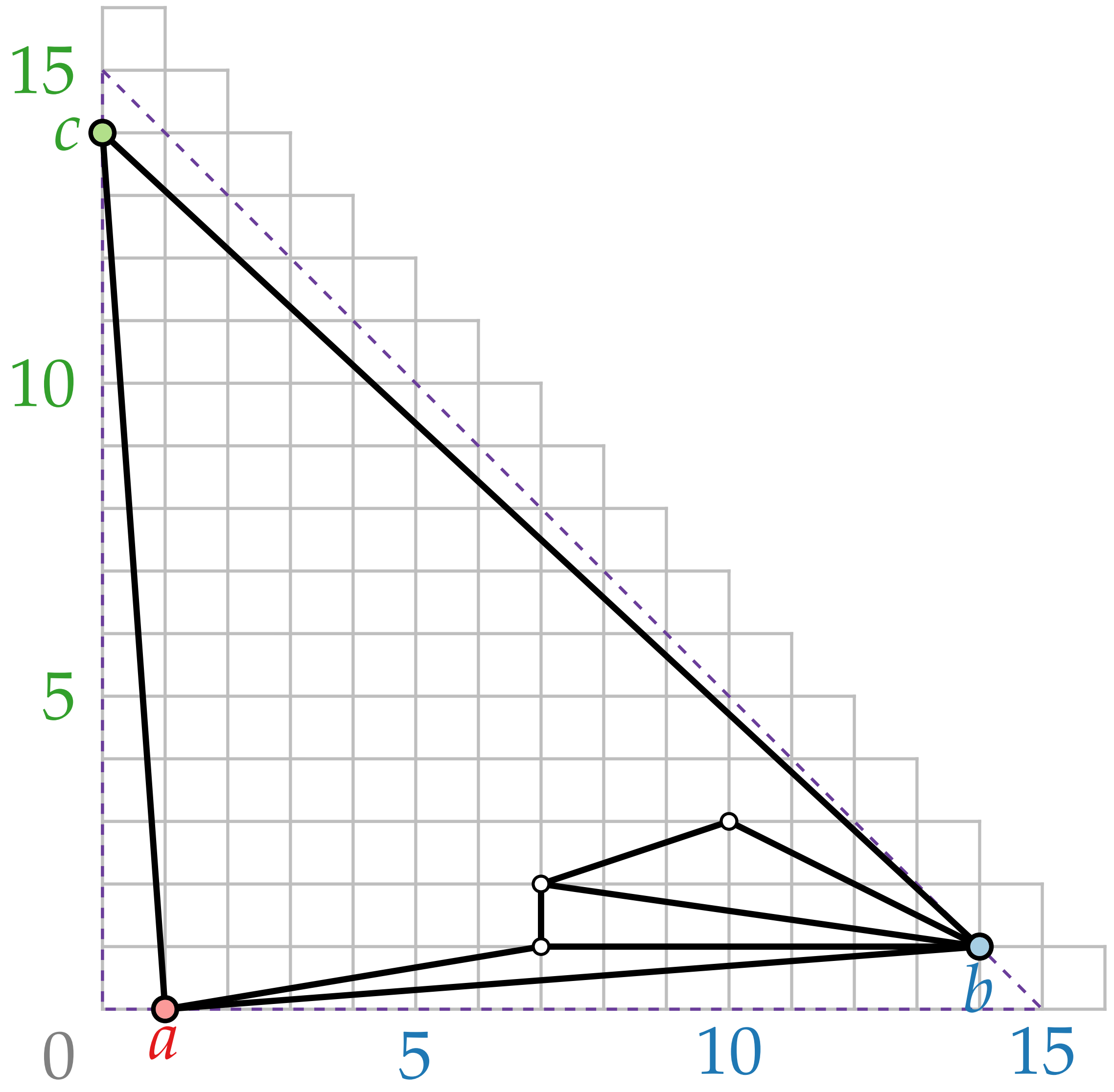

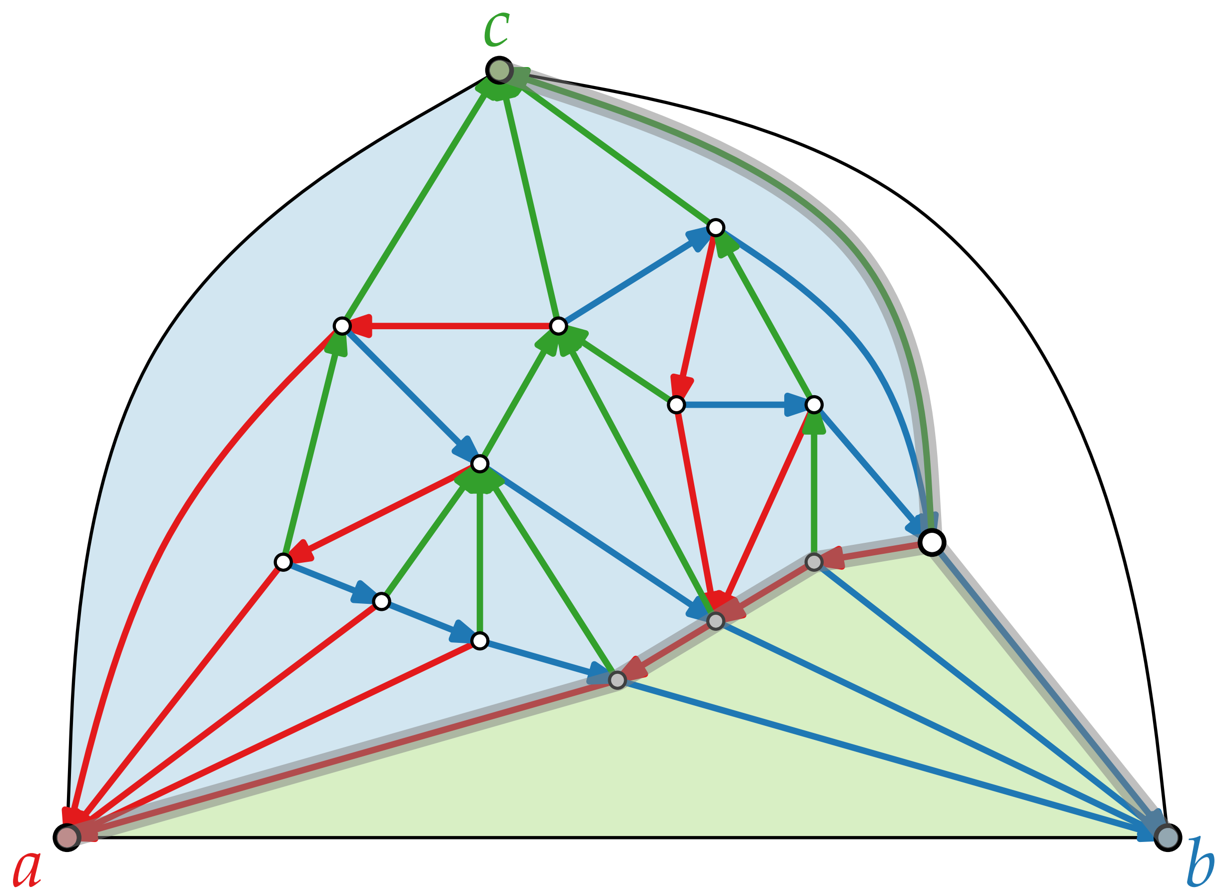

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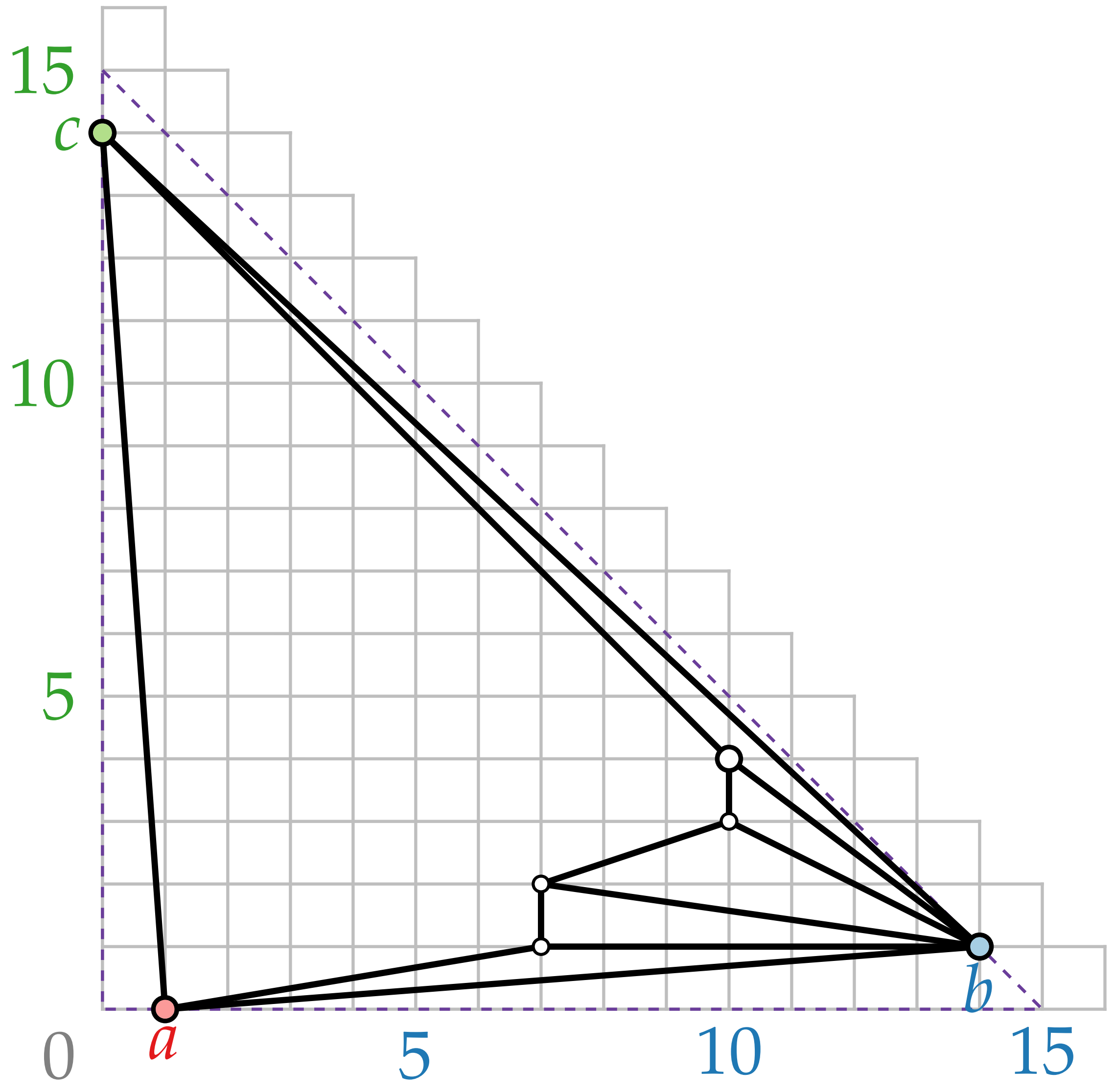

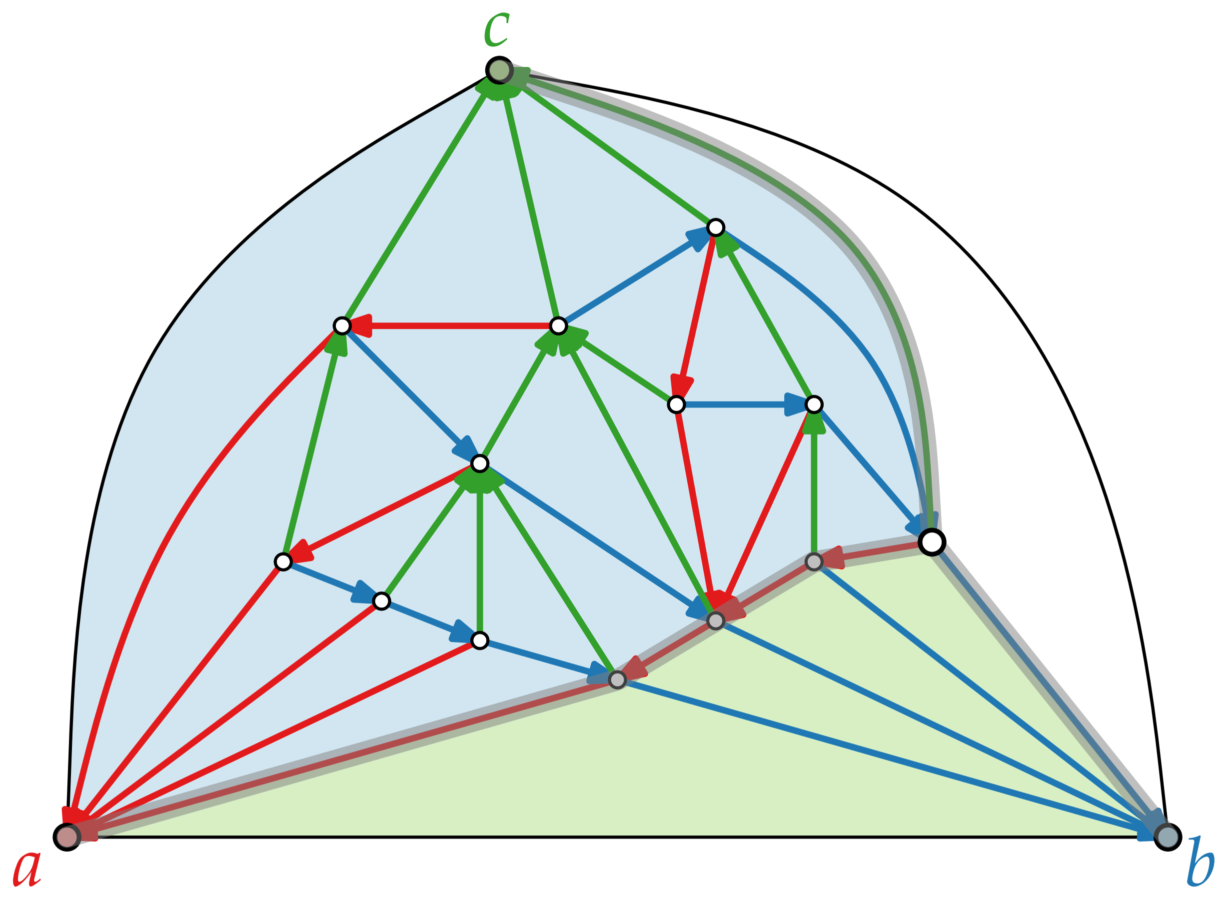

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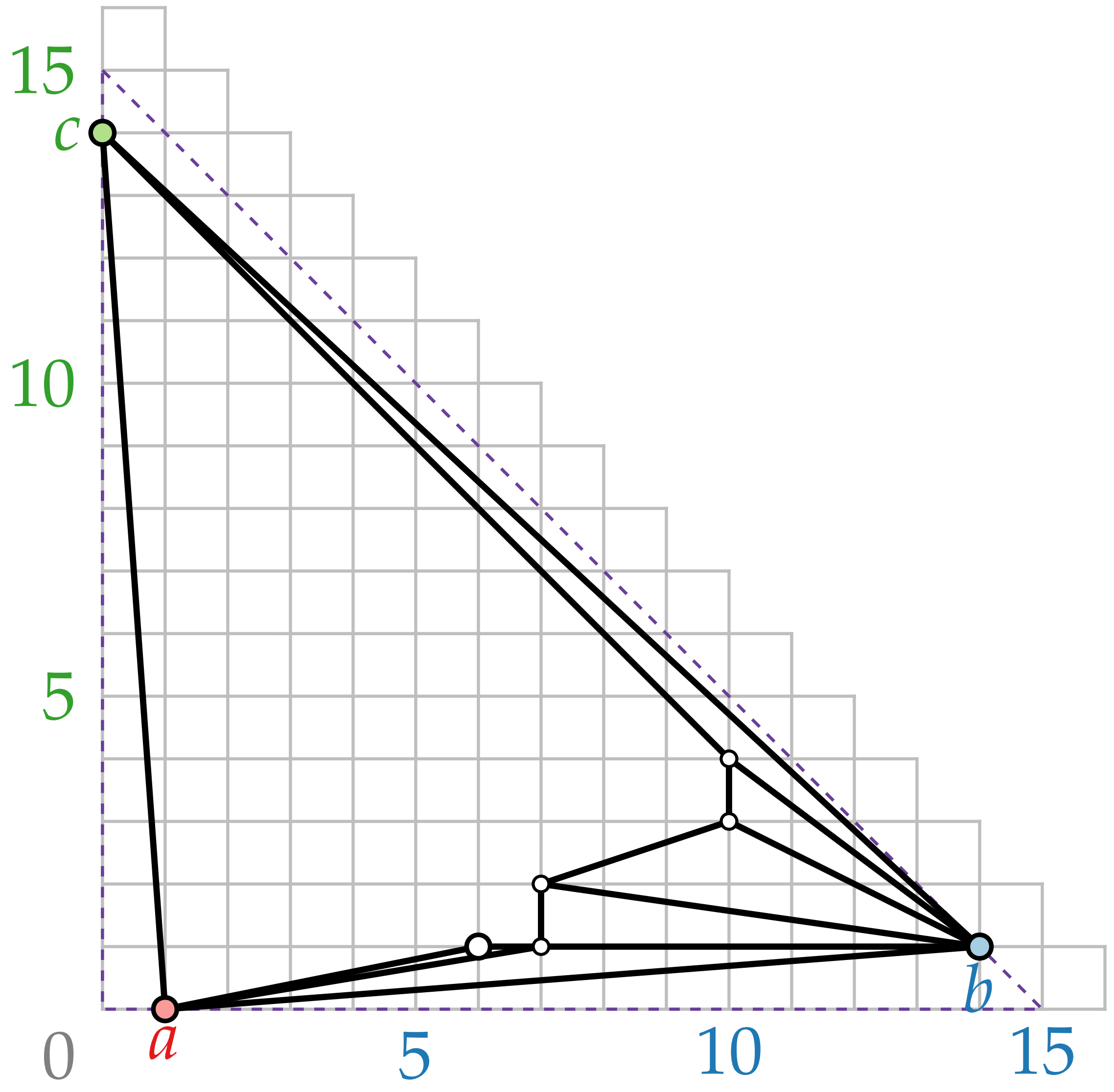

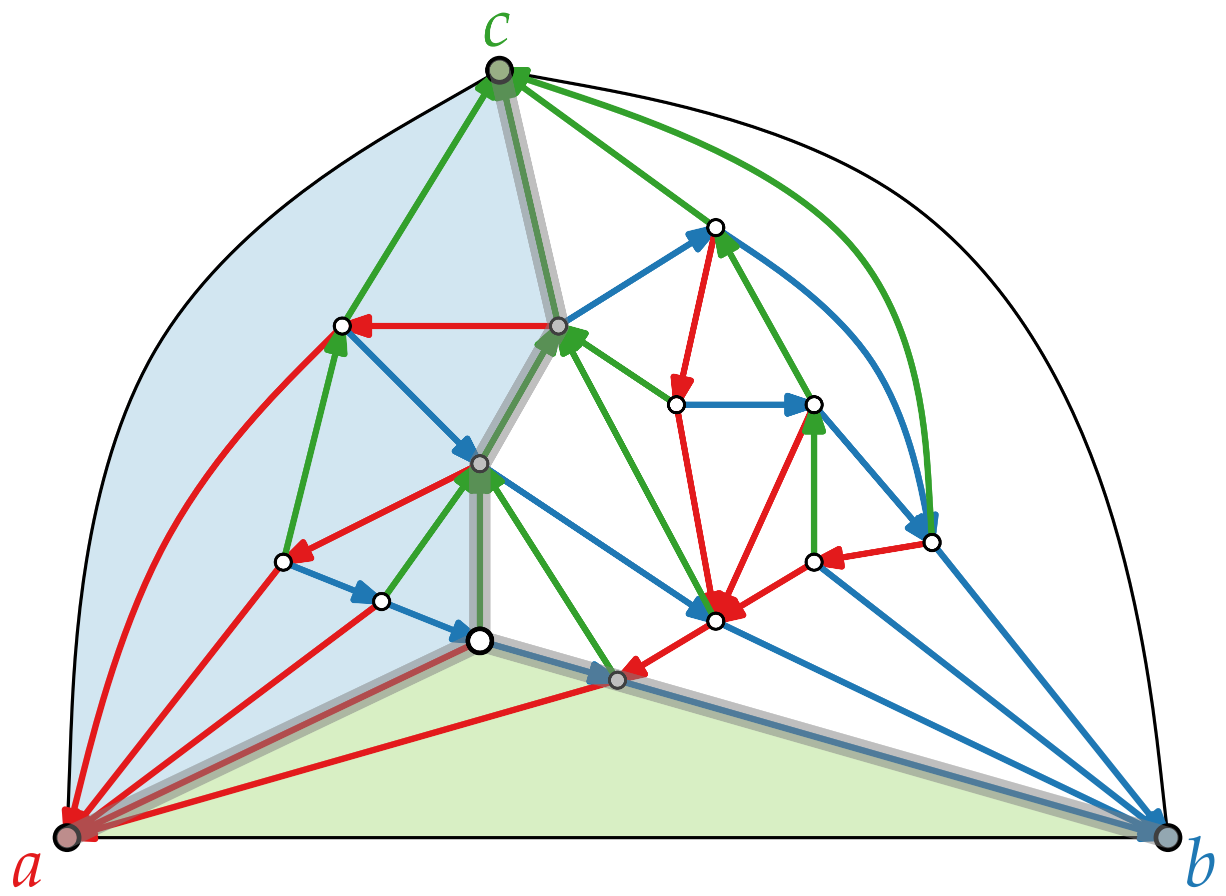

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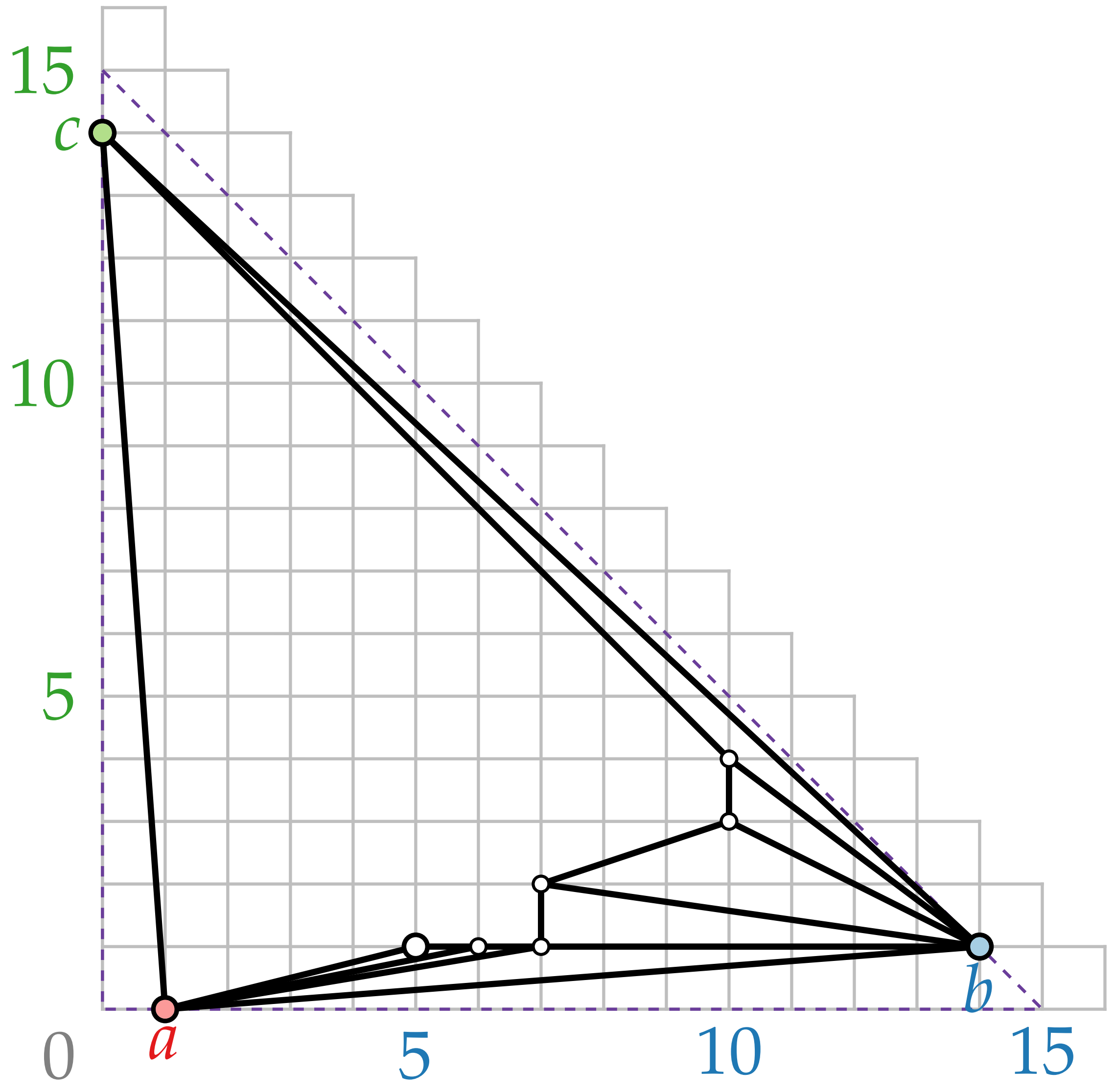

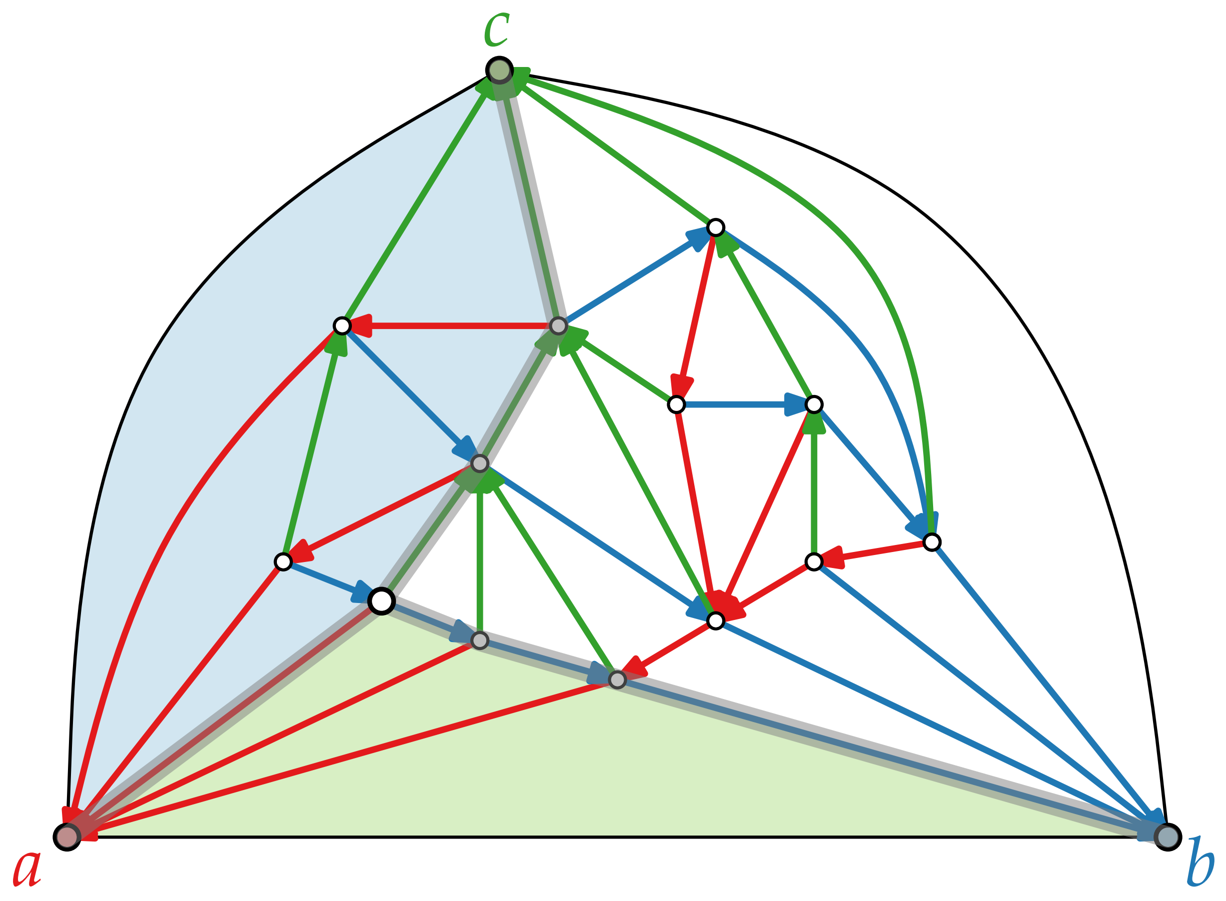

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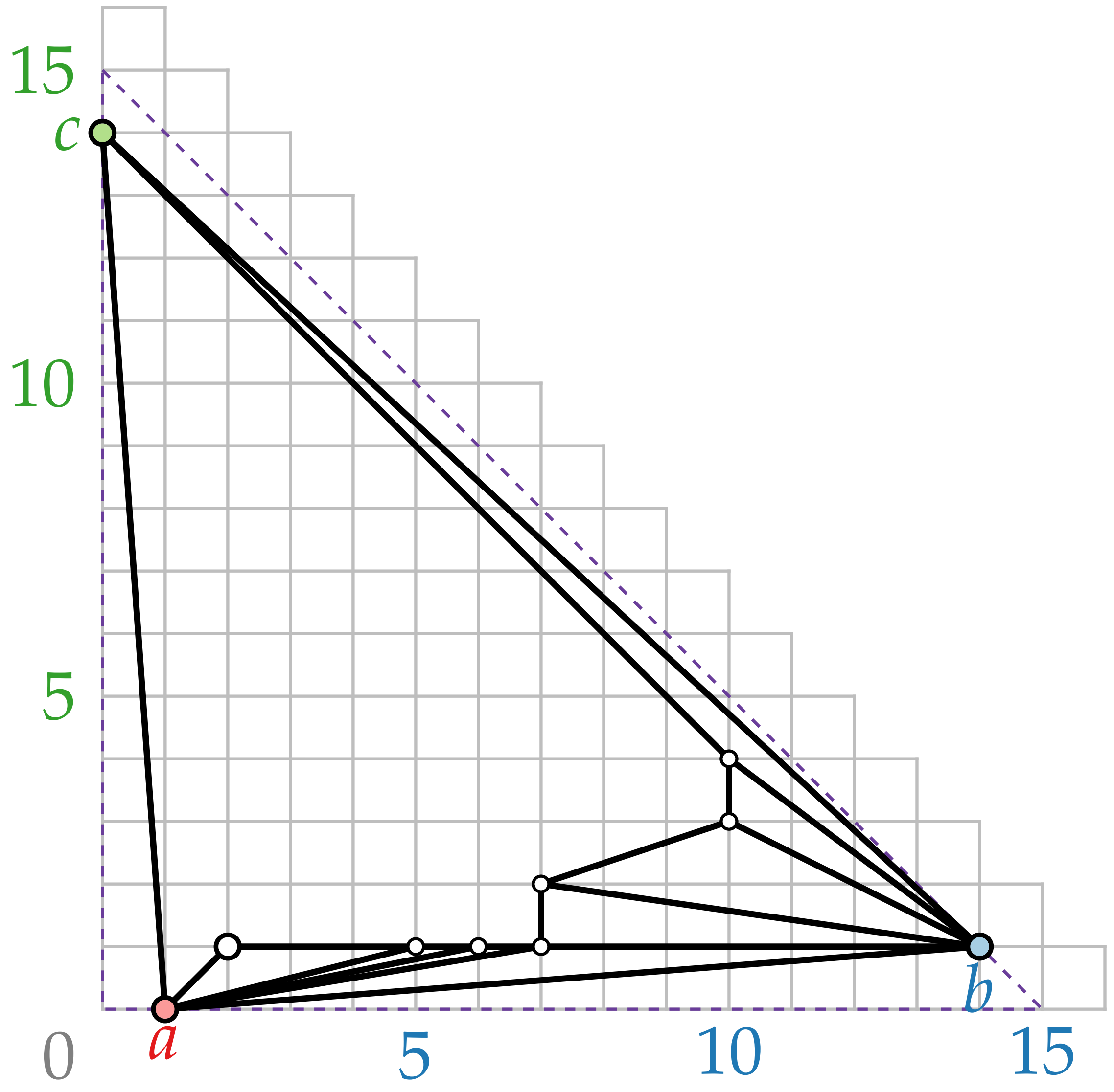

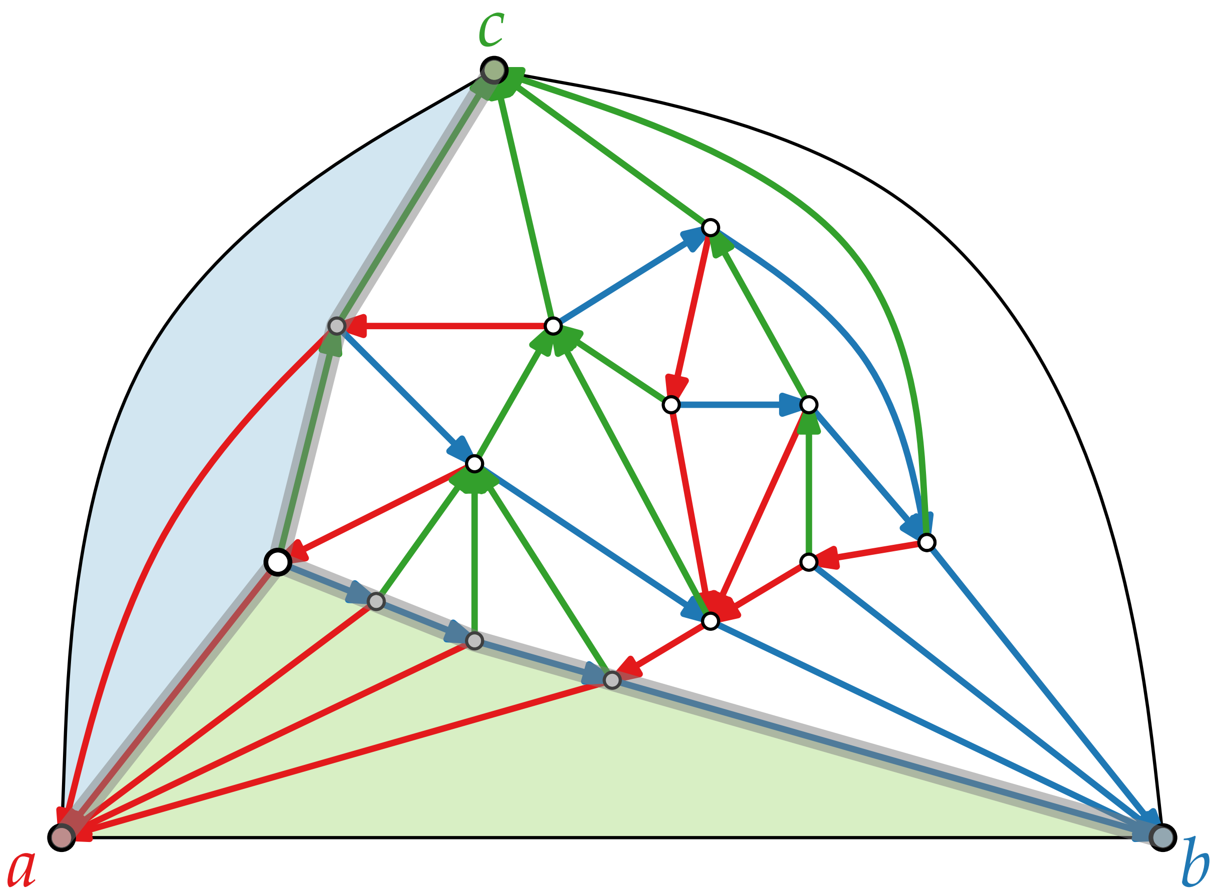

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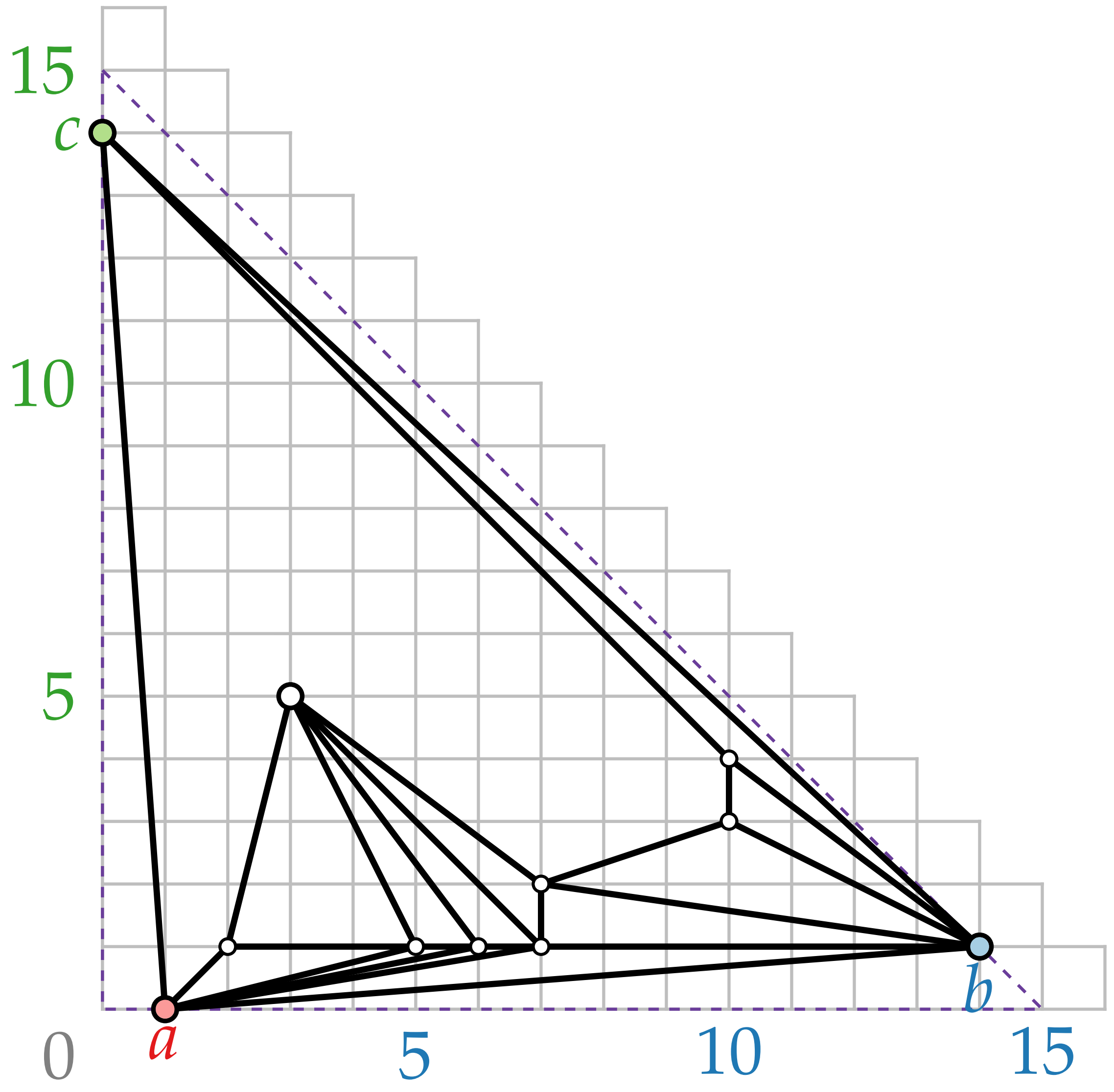

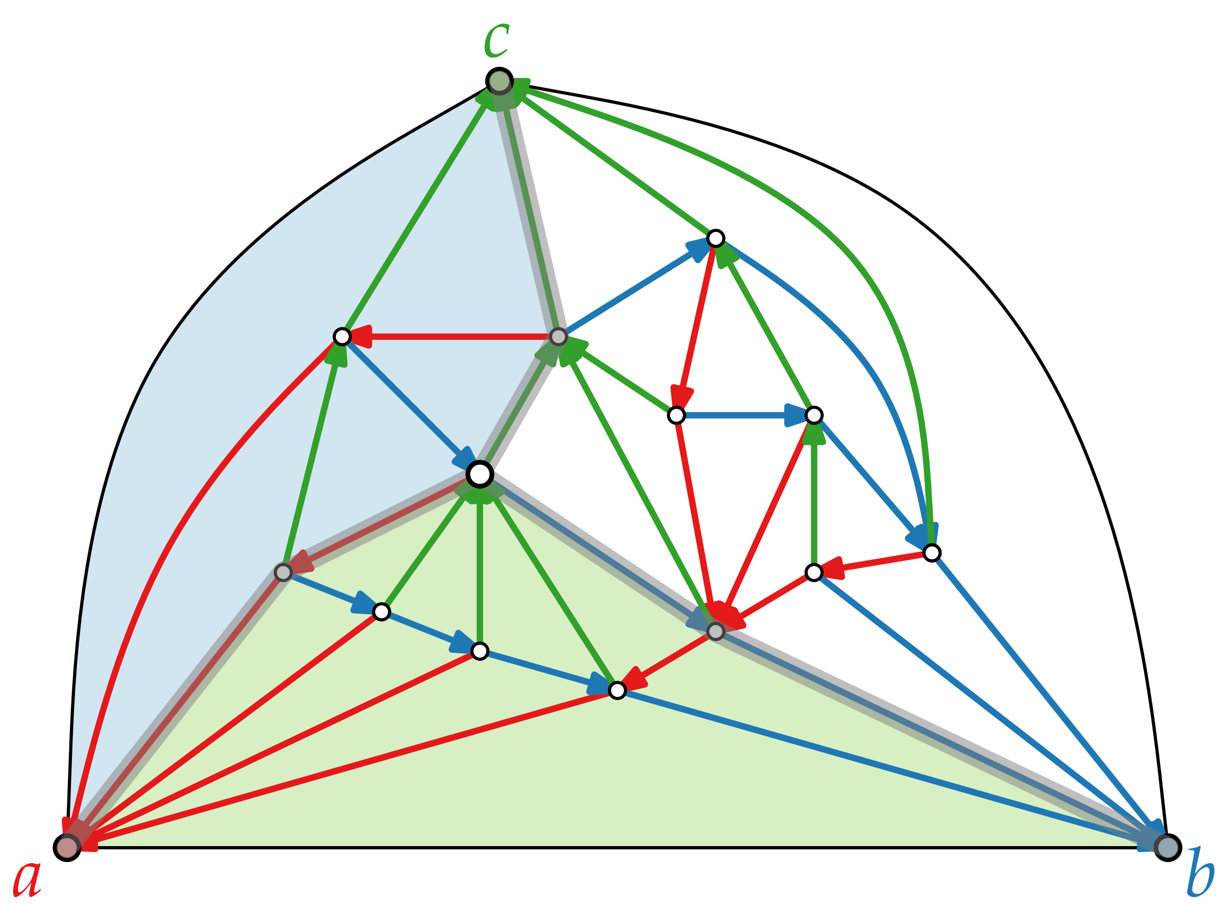

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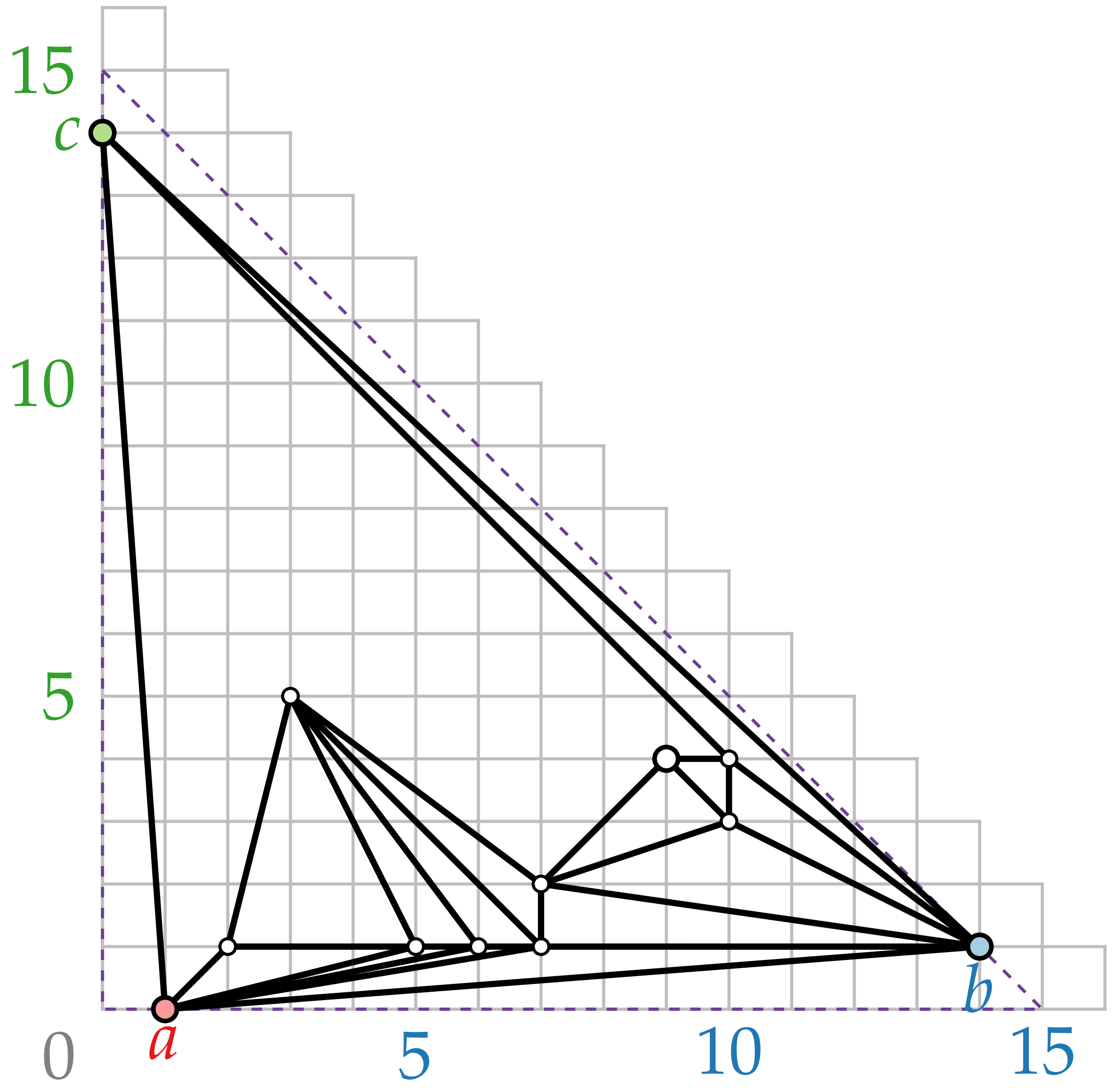

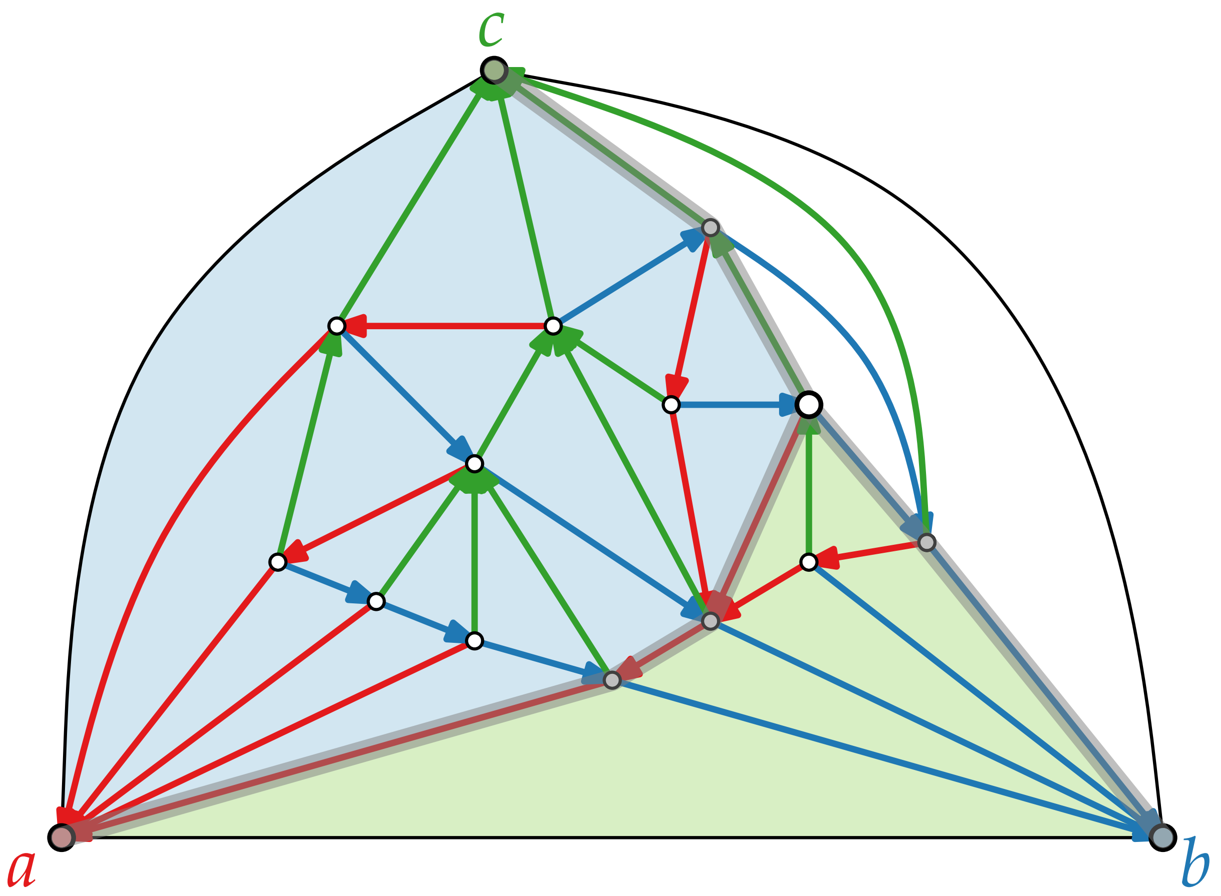

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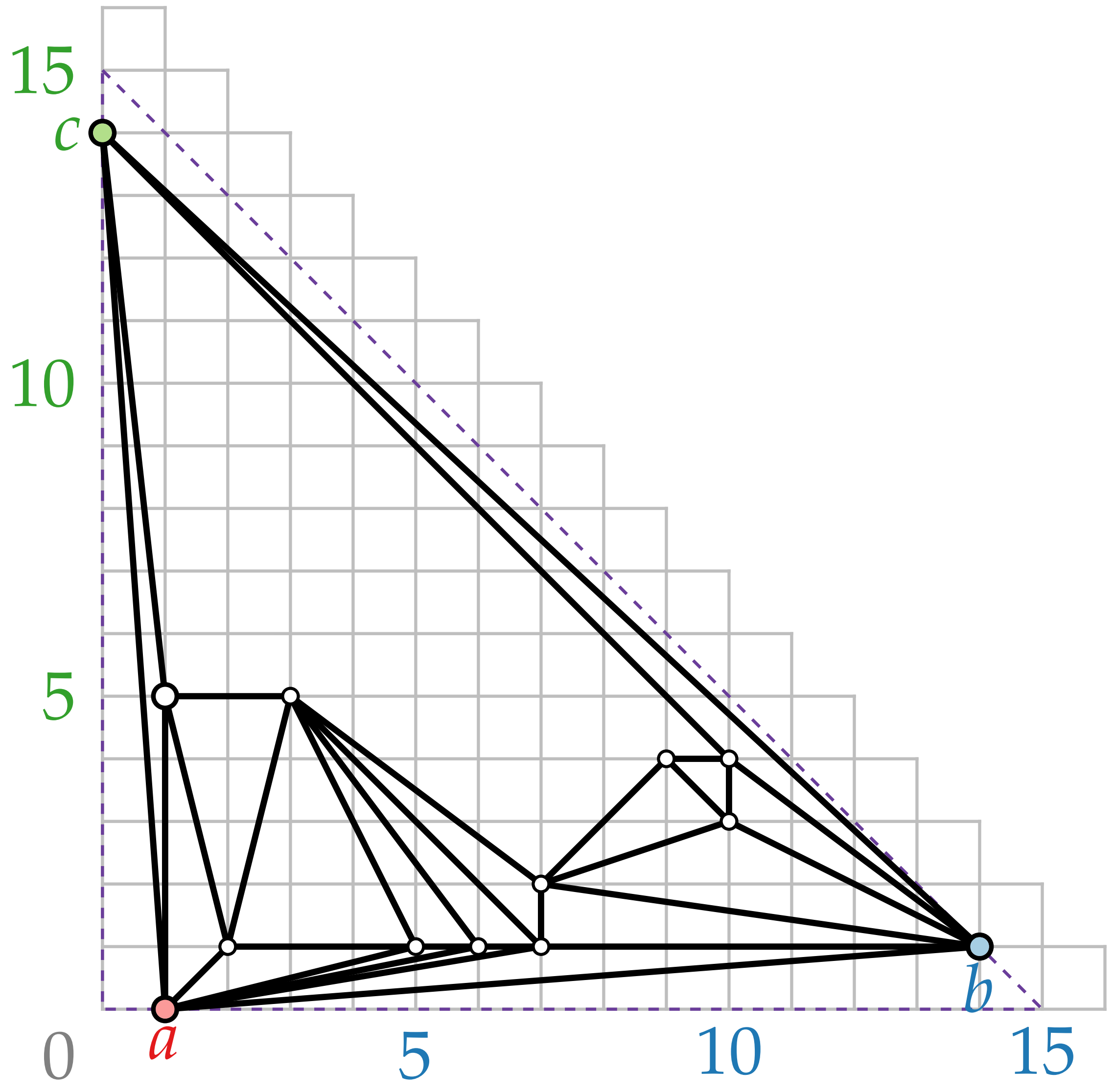

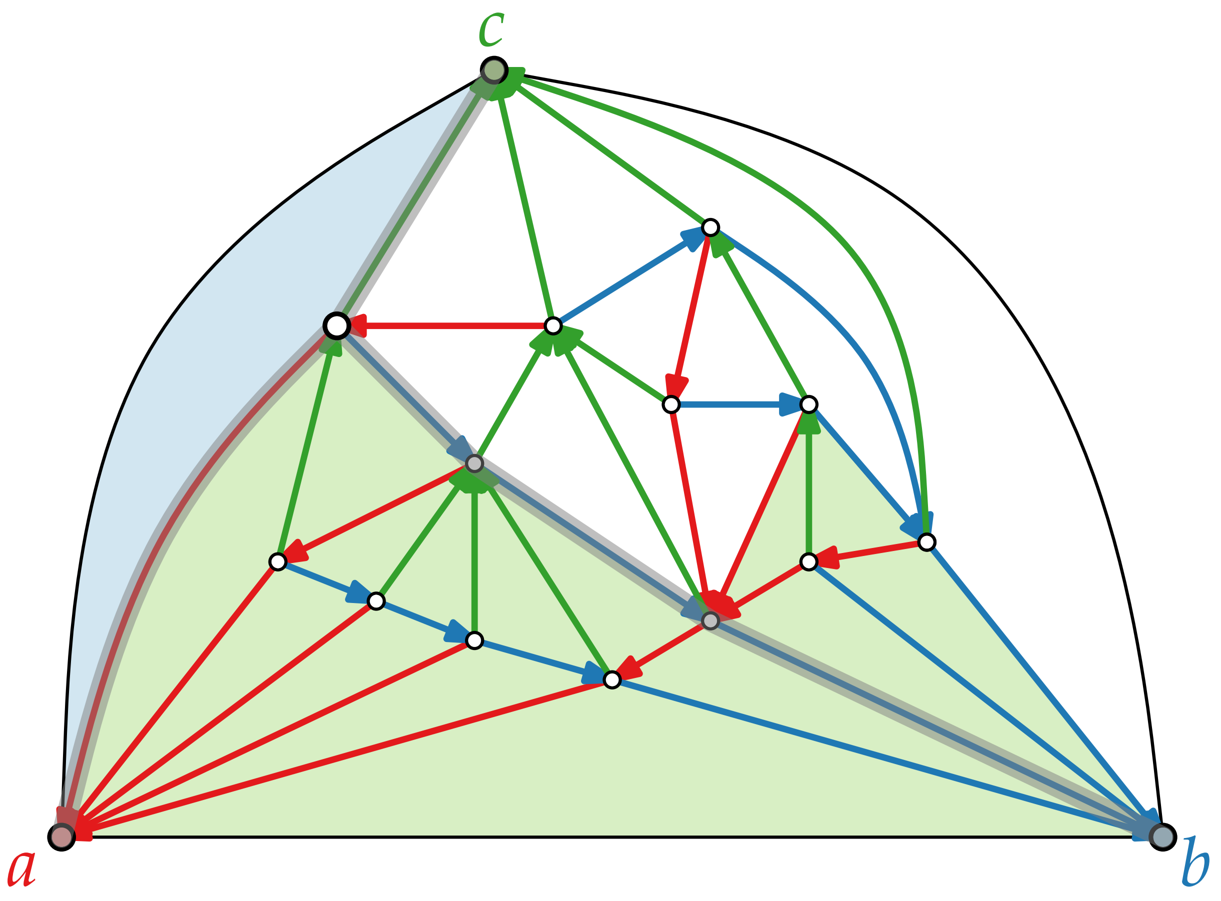

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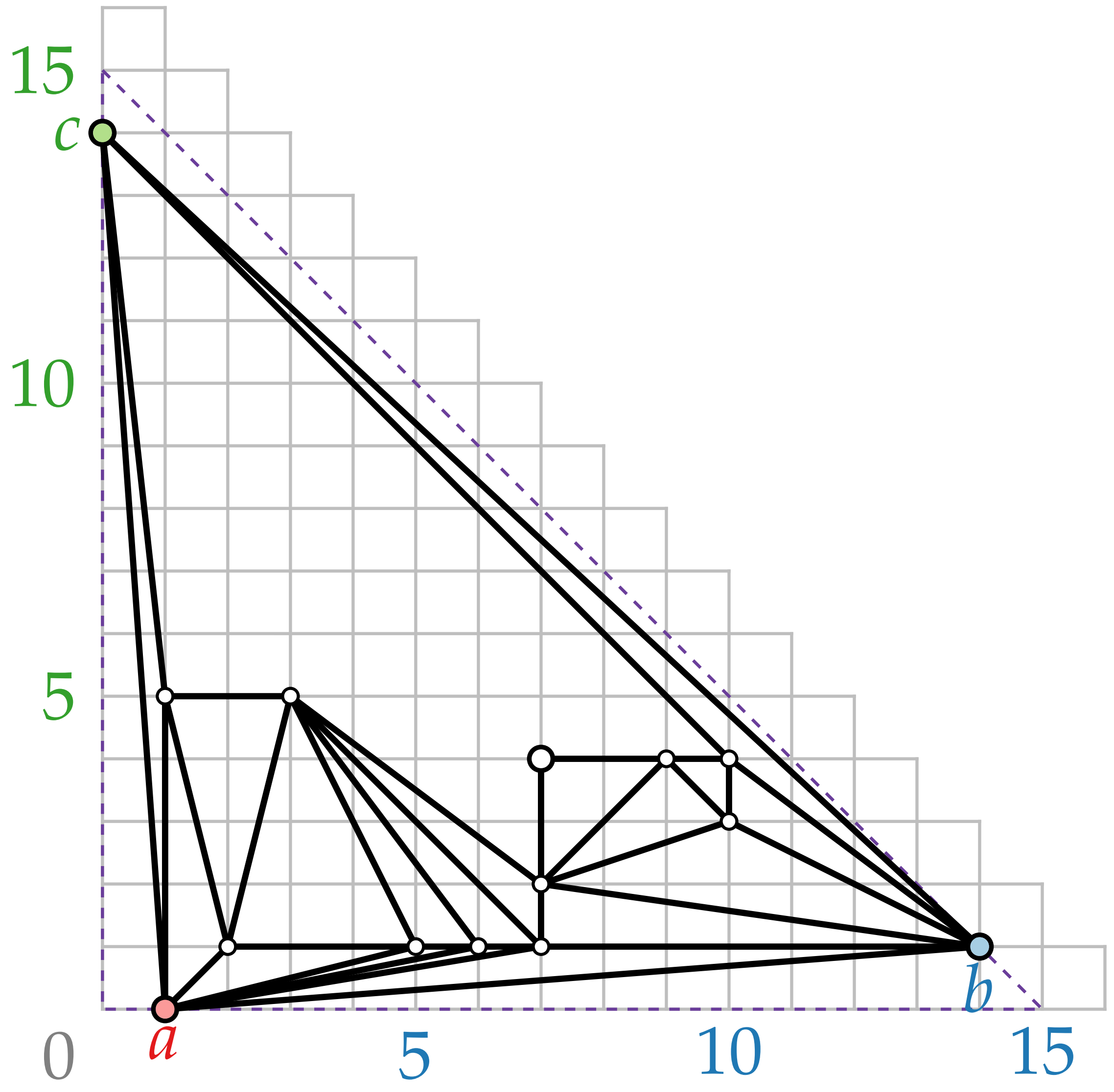

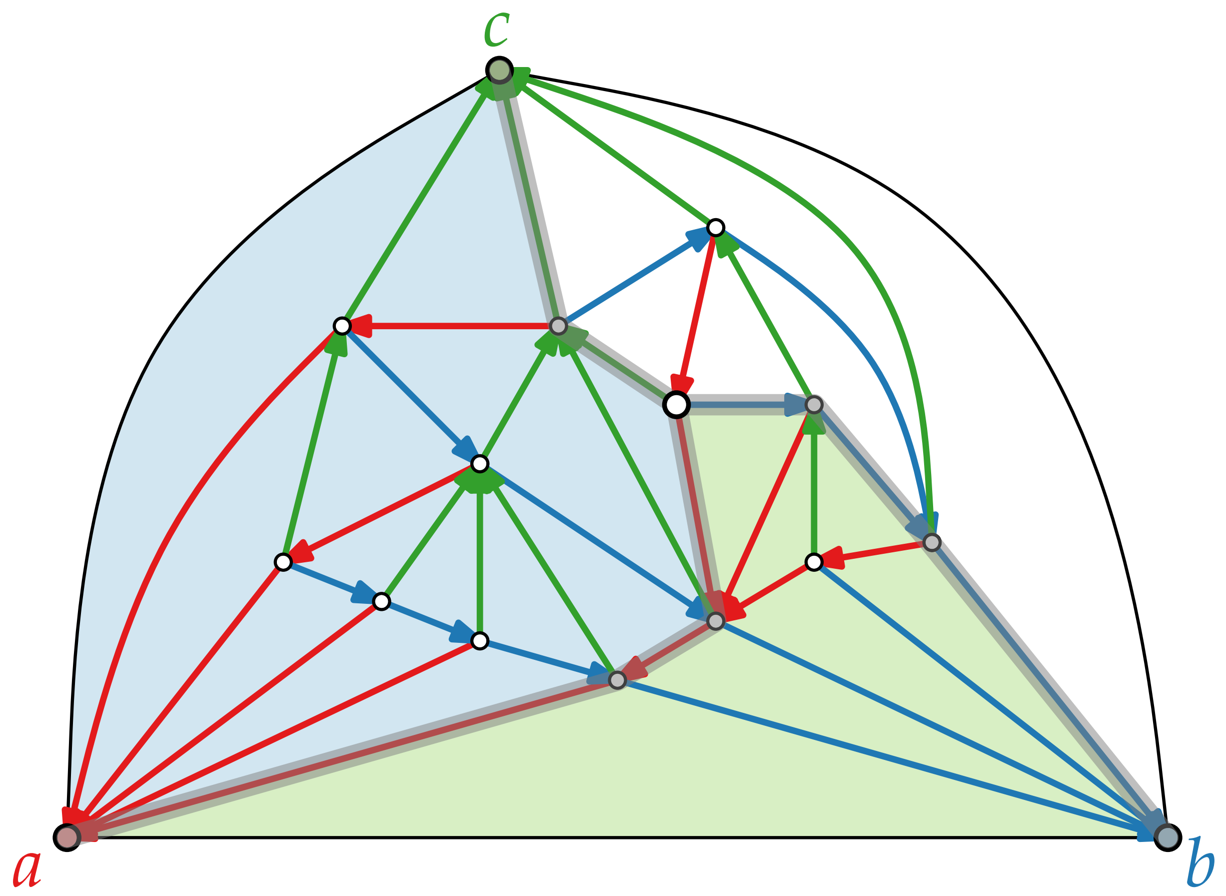

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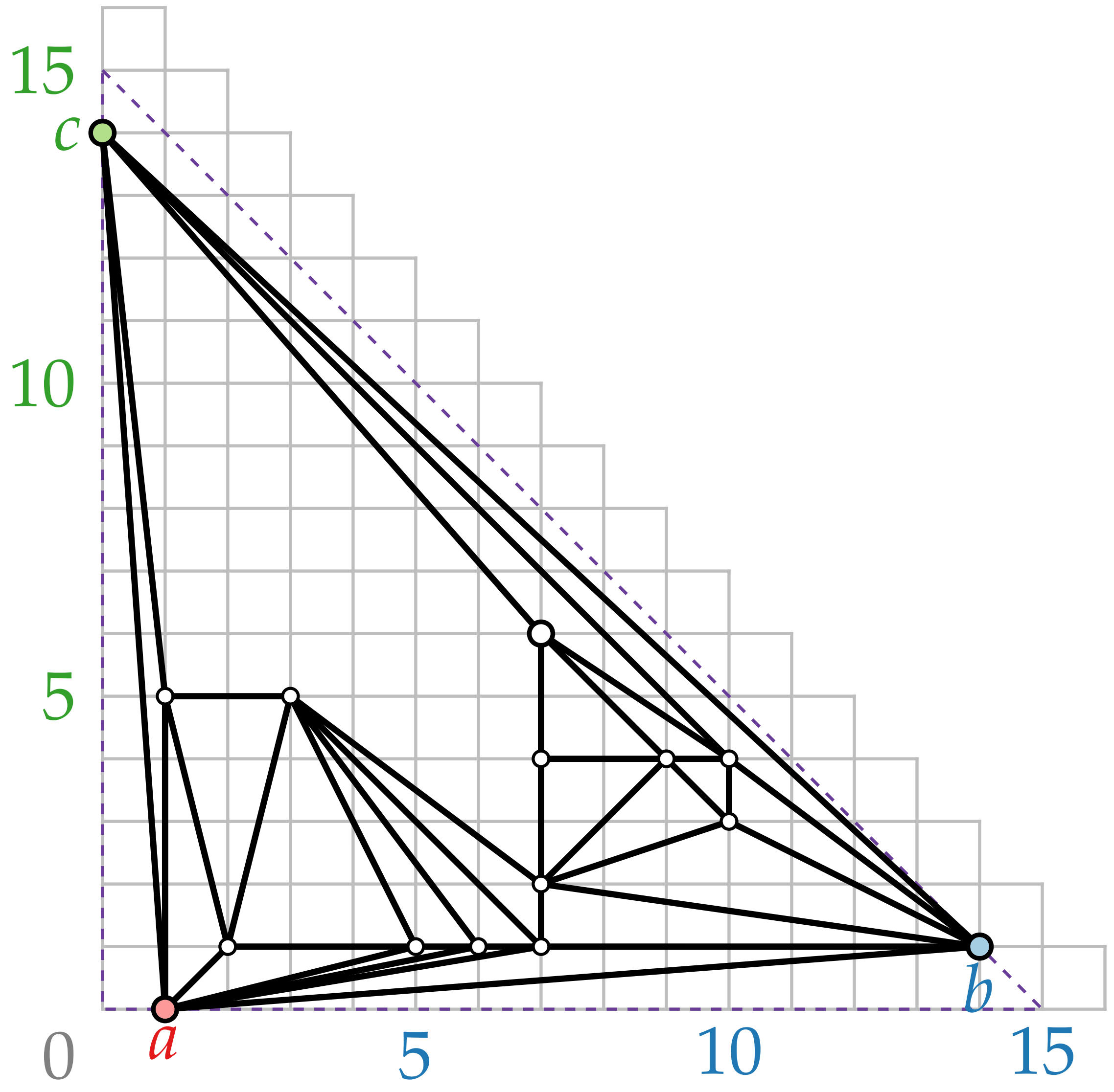

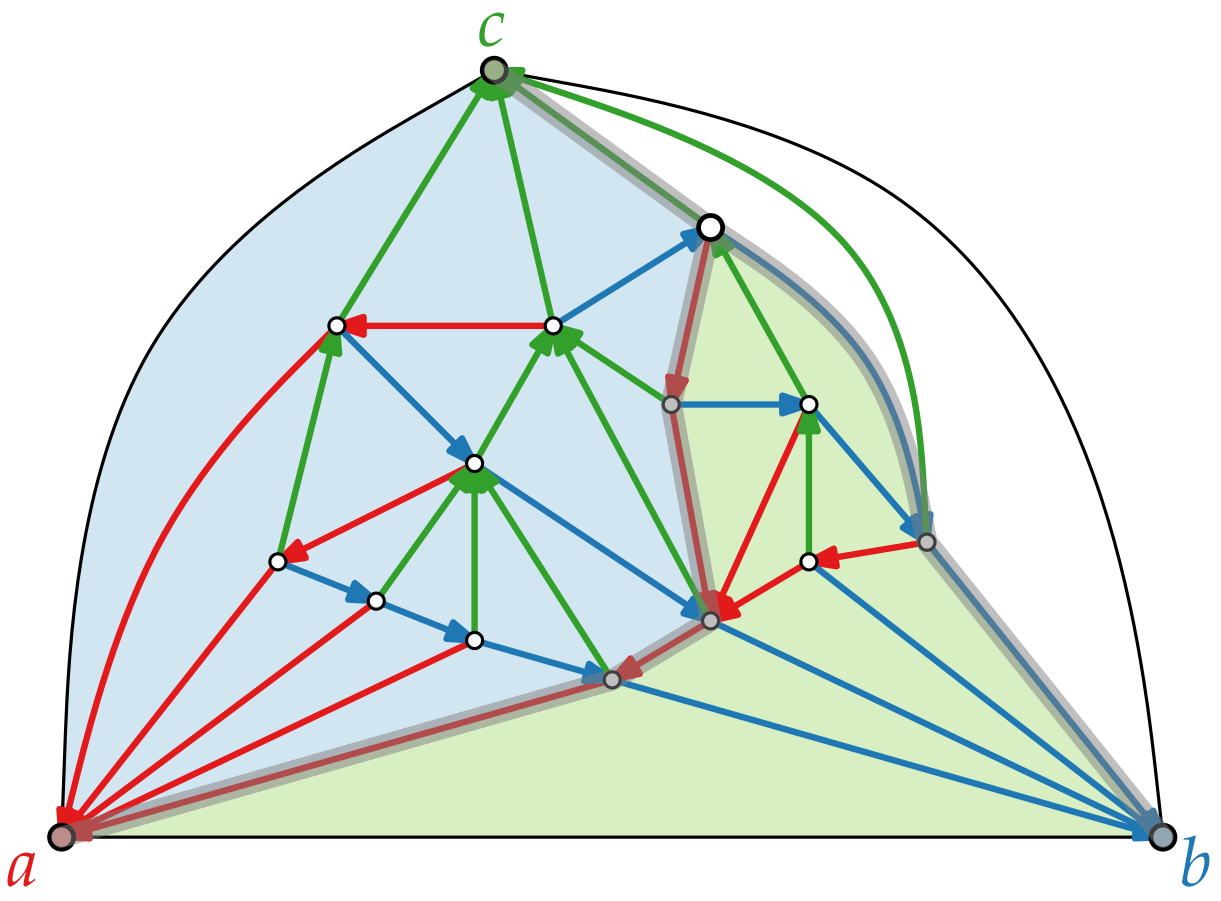

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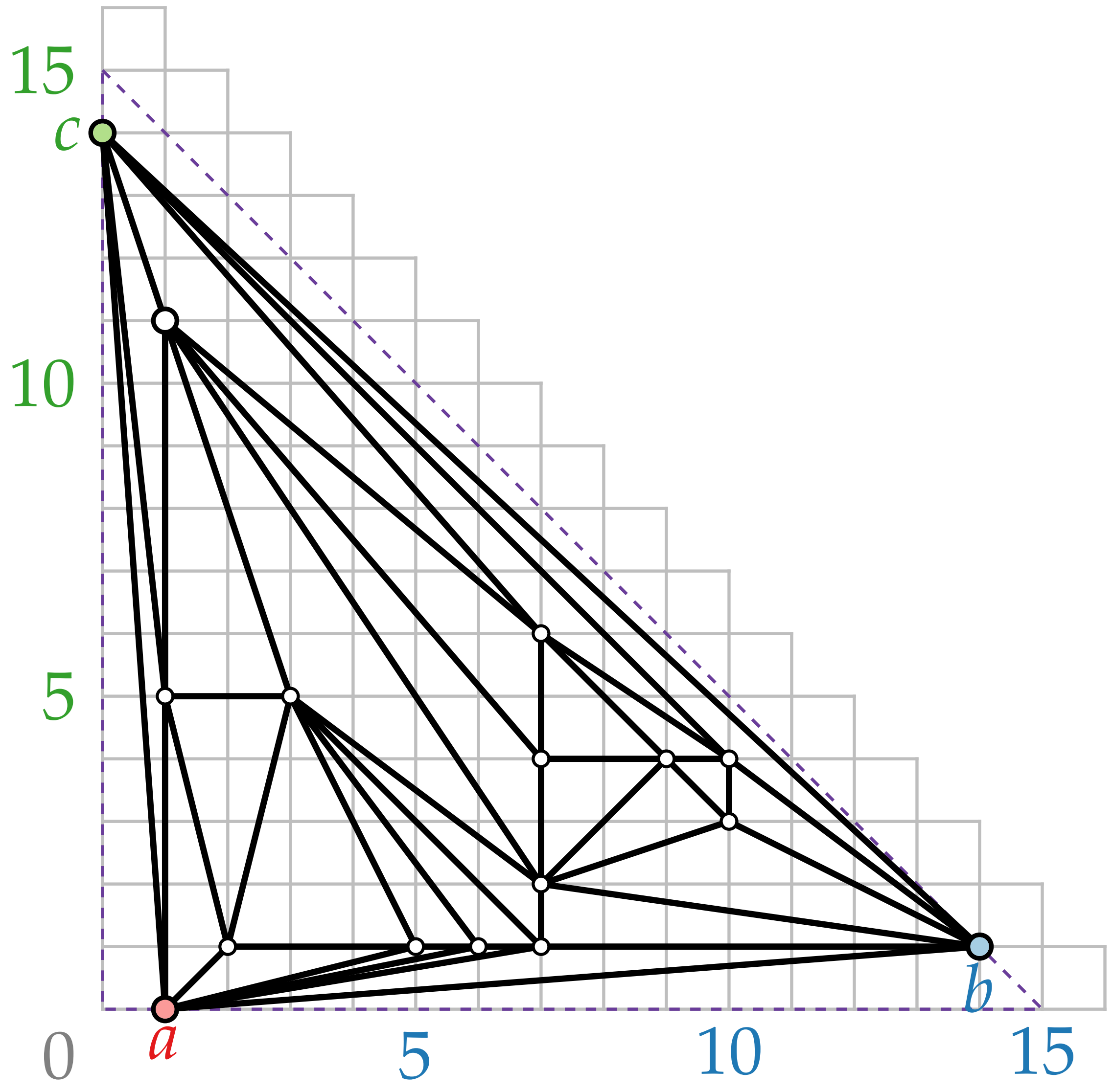

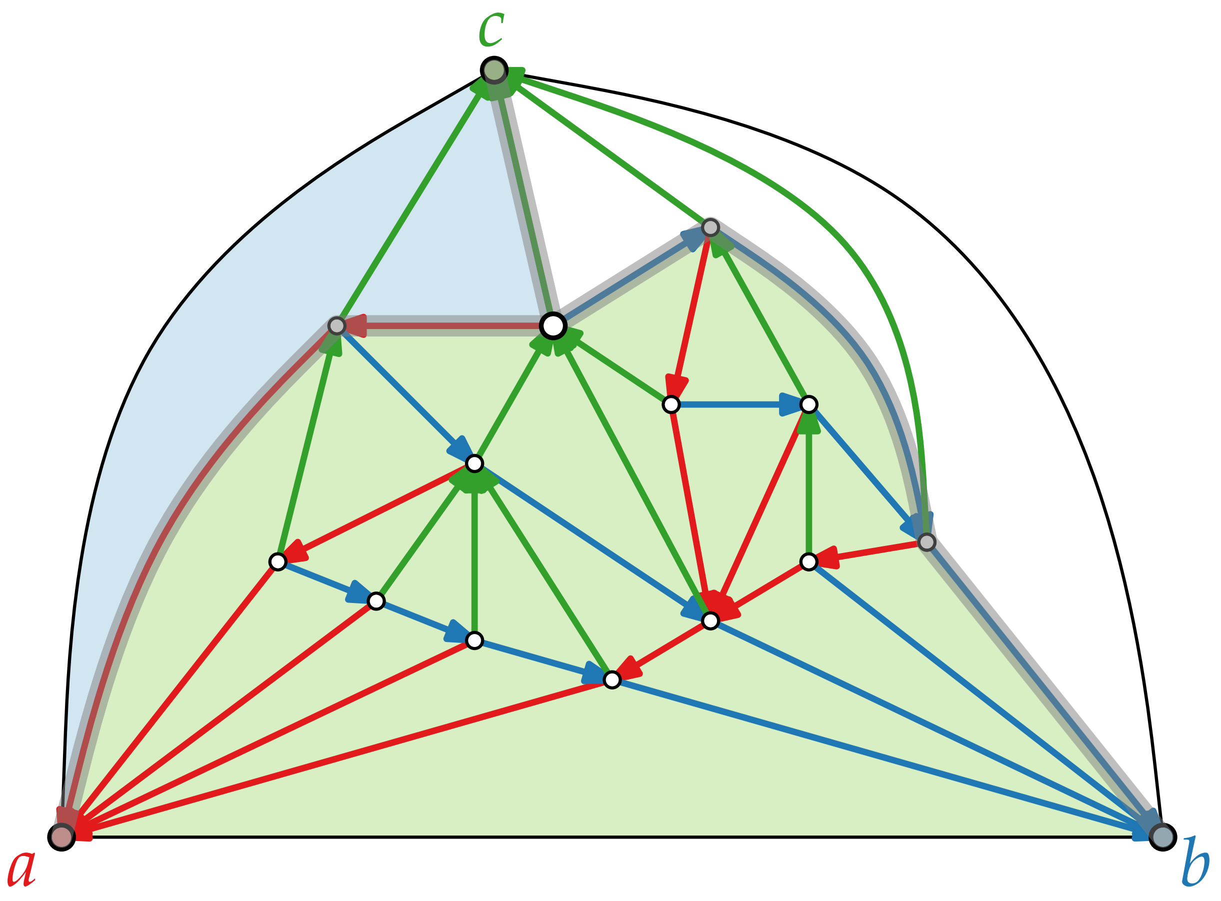

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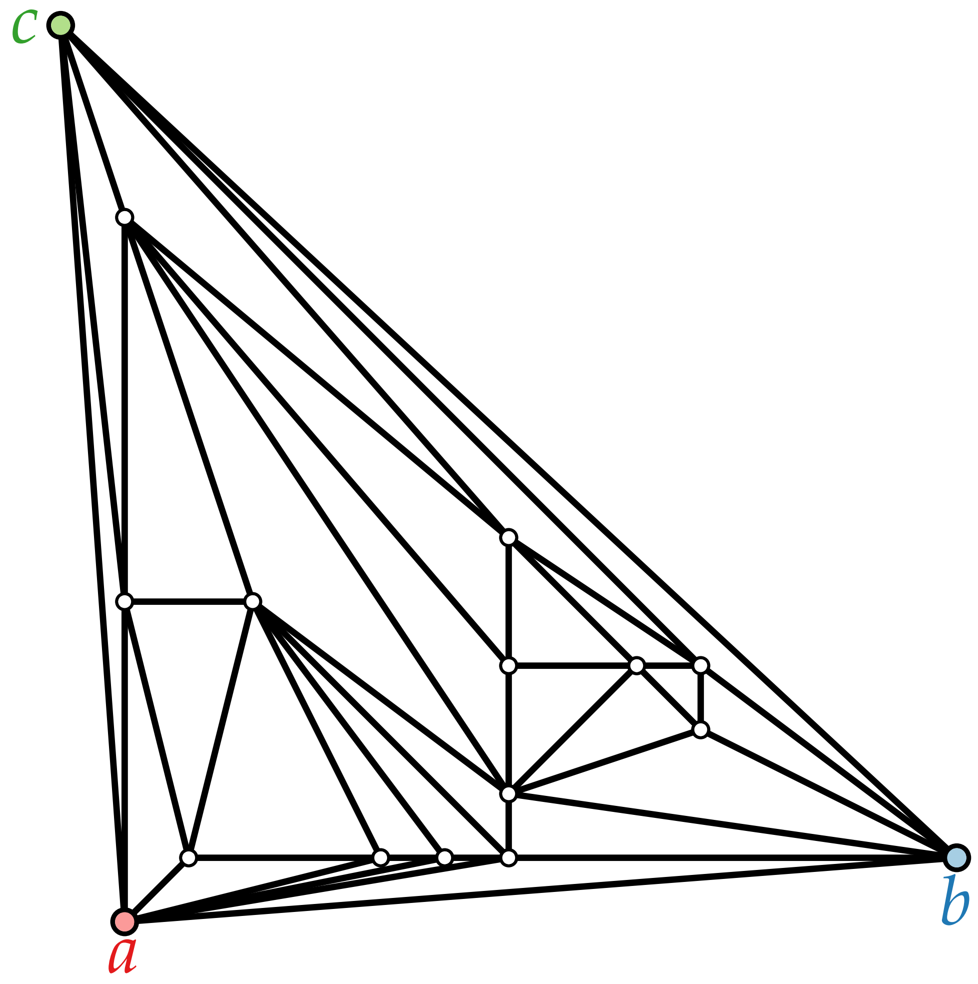

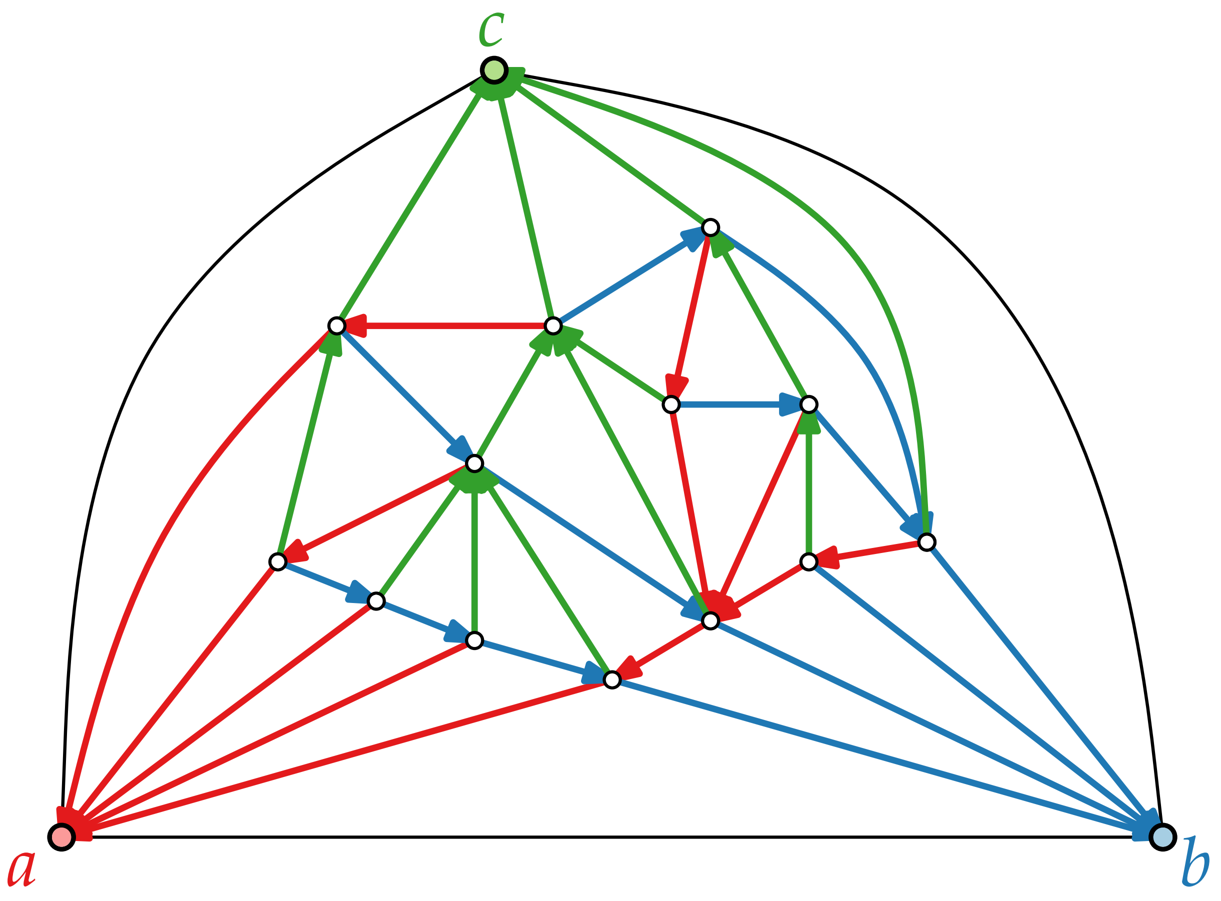

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Results & Variations

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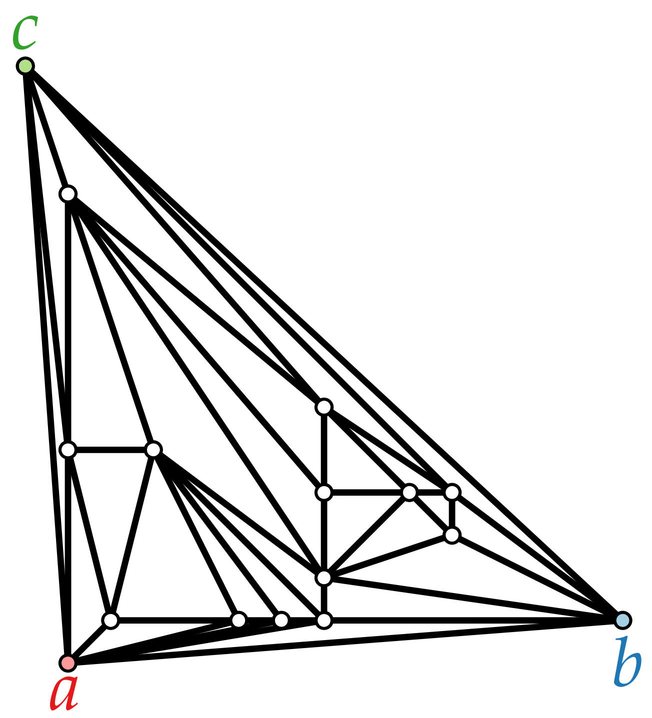

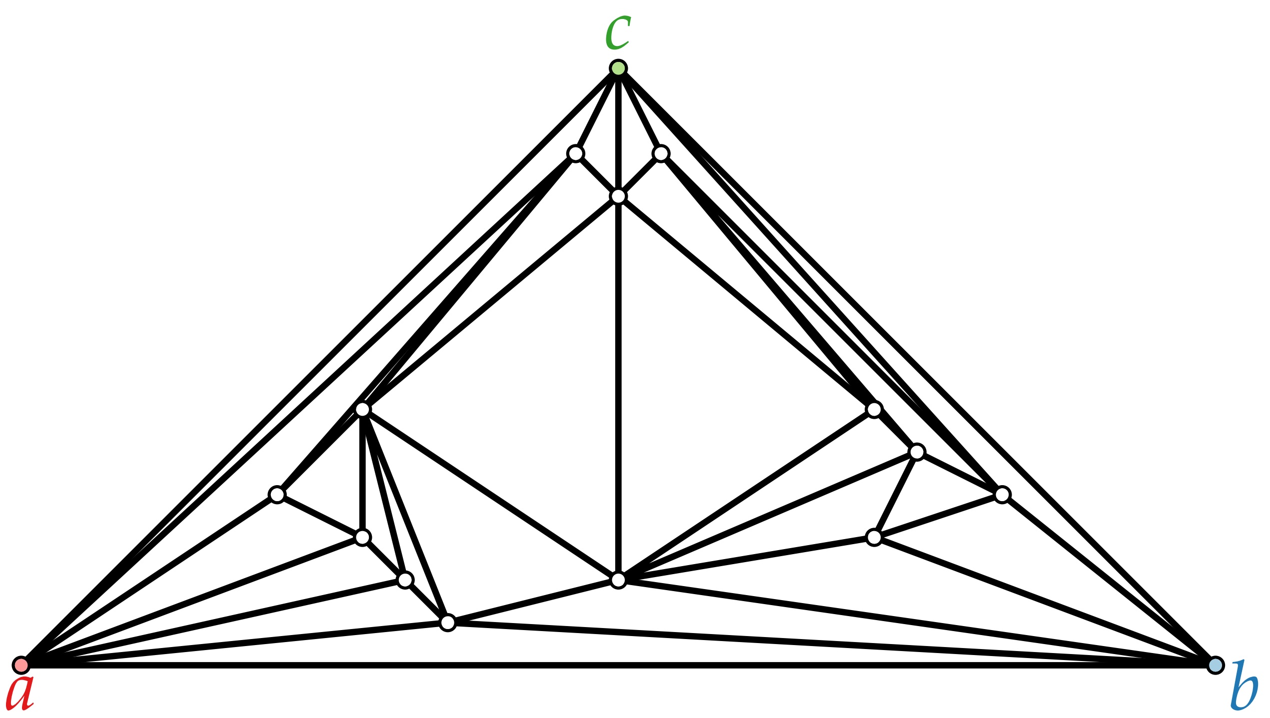

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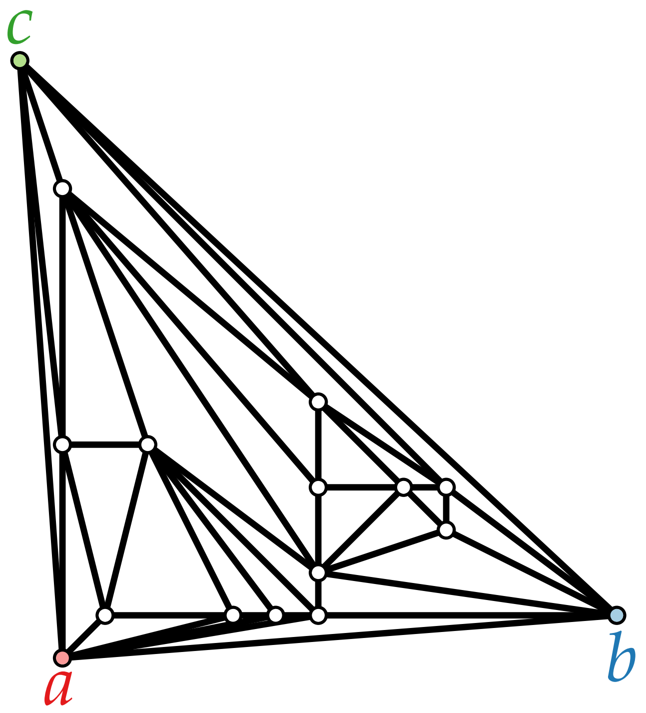

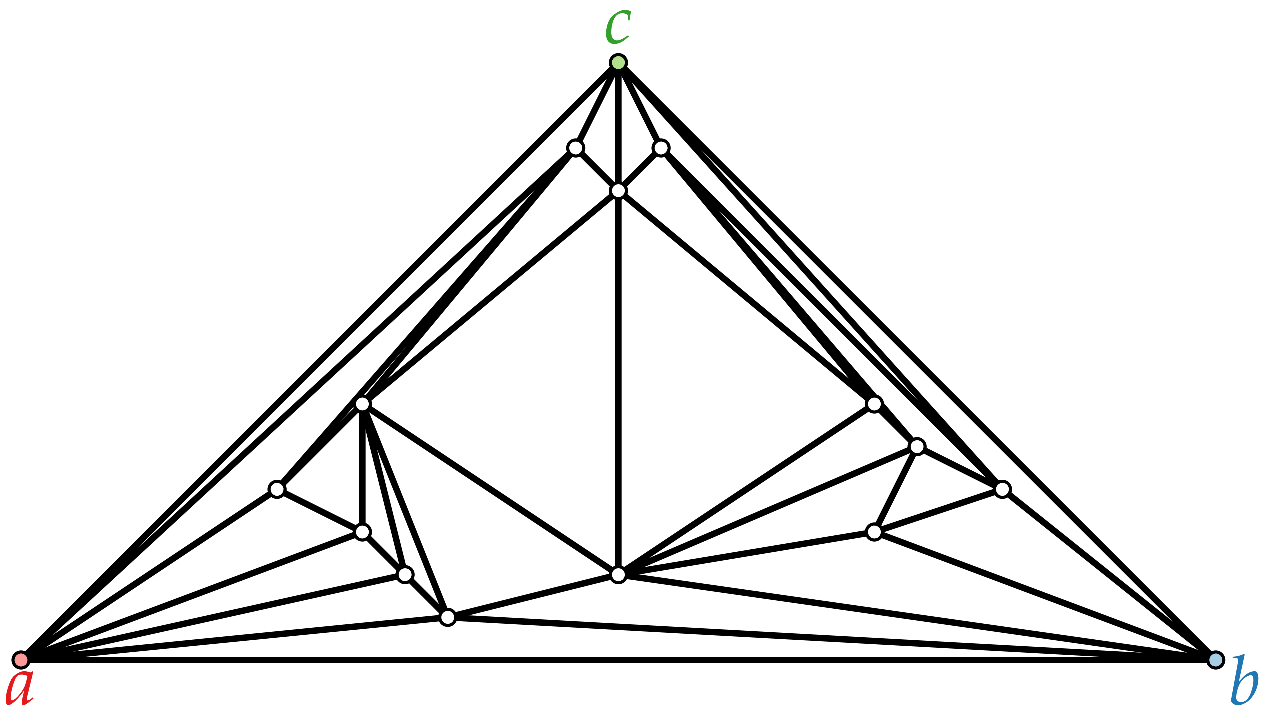

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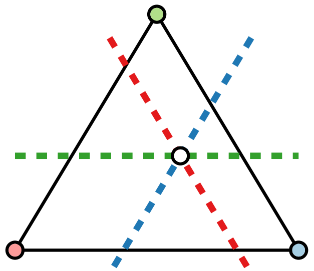
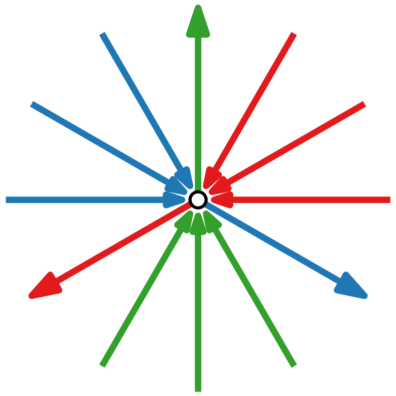
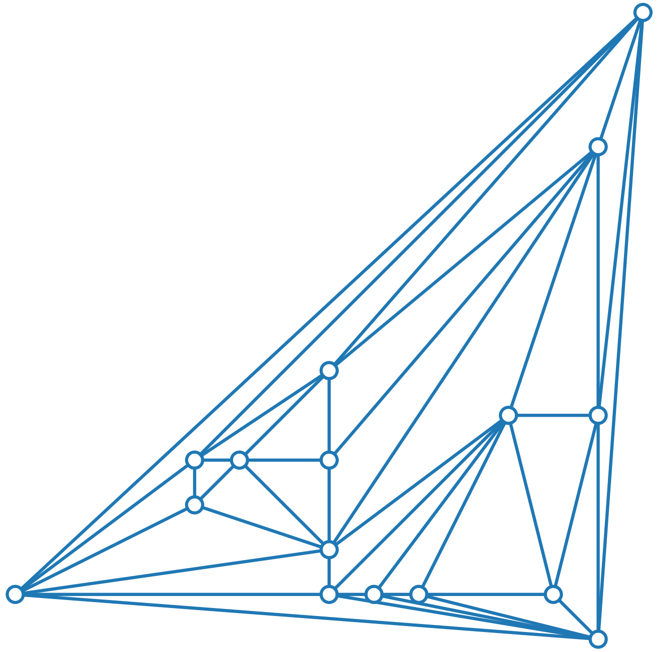


Visualization of Graphs



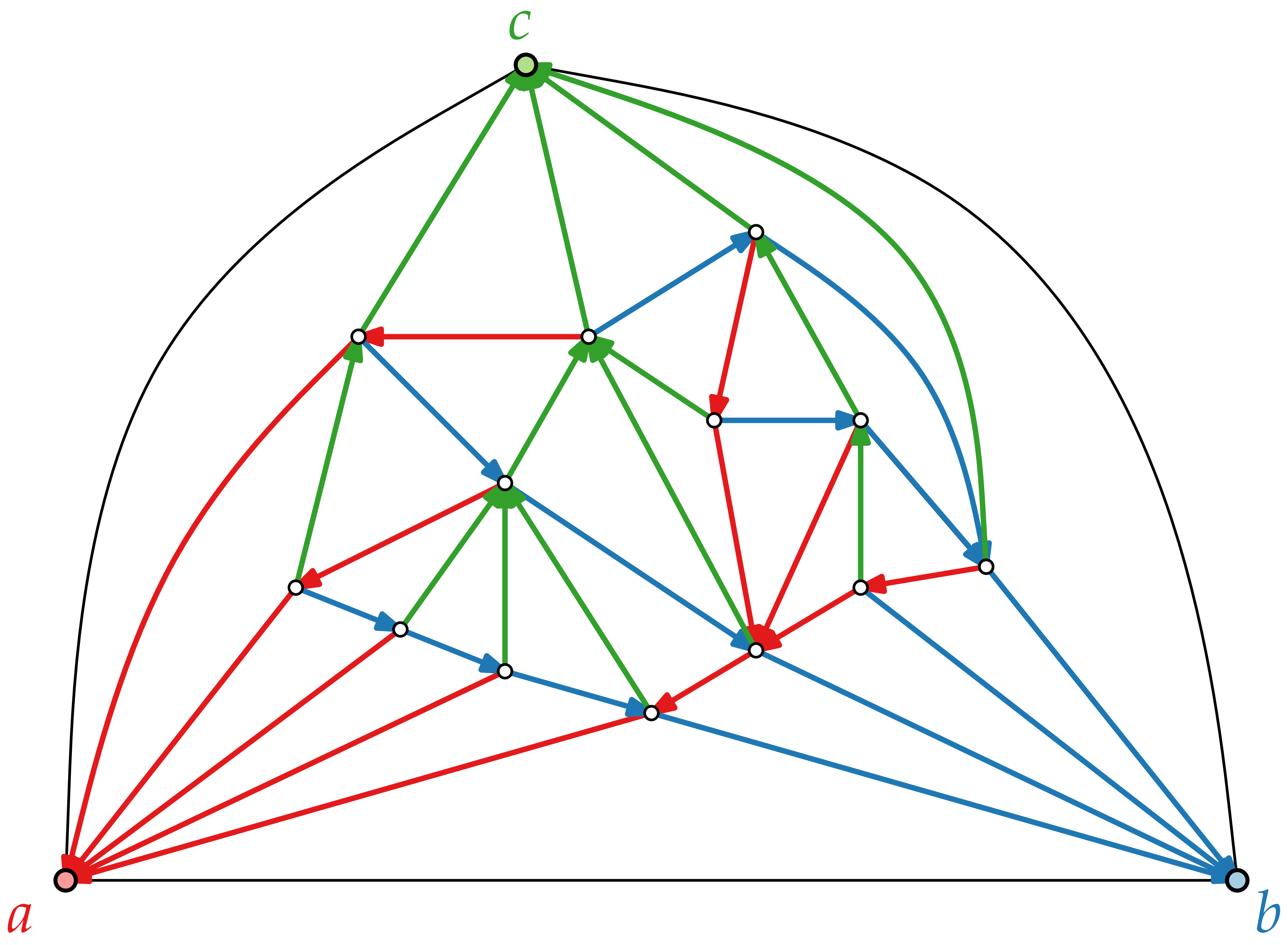
Lecture 5:
Straight-Line Drawings of Planar Graphs II: Schnyder Woods



Part V:
From Schnyder to Canonical Order
. . . and back again

Philipp Kindermann

Schnyder Realizer → Canonical Order



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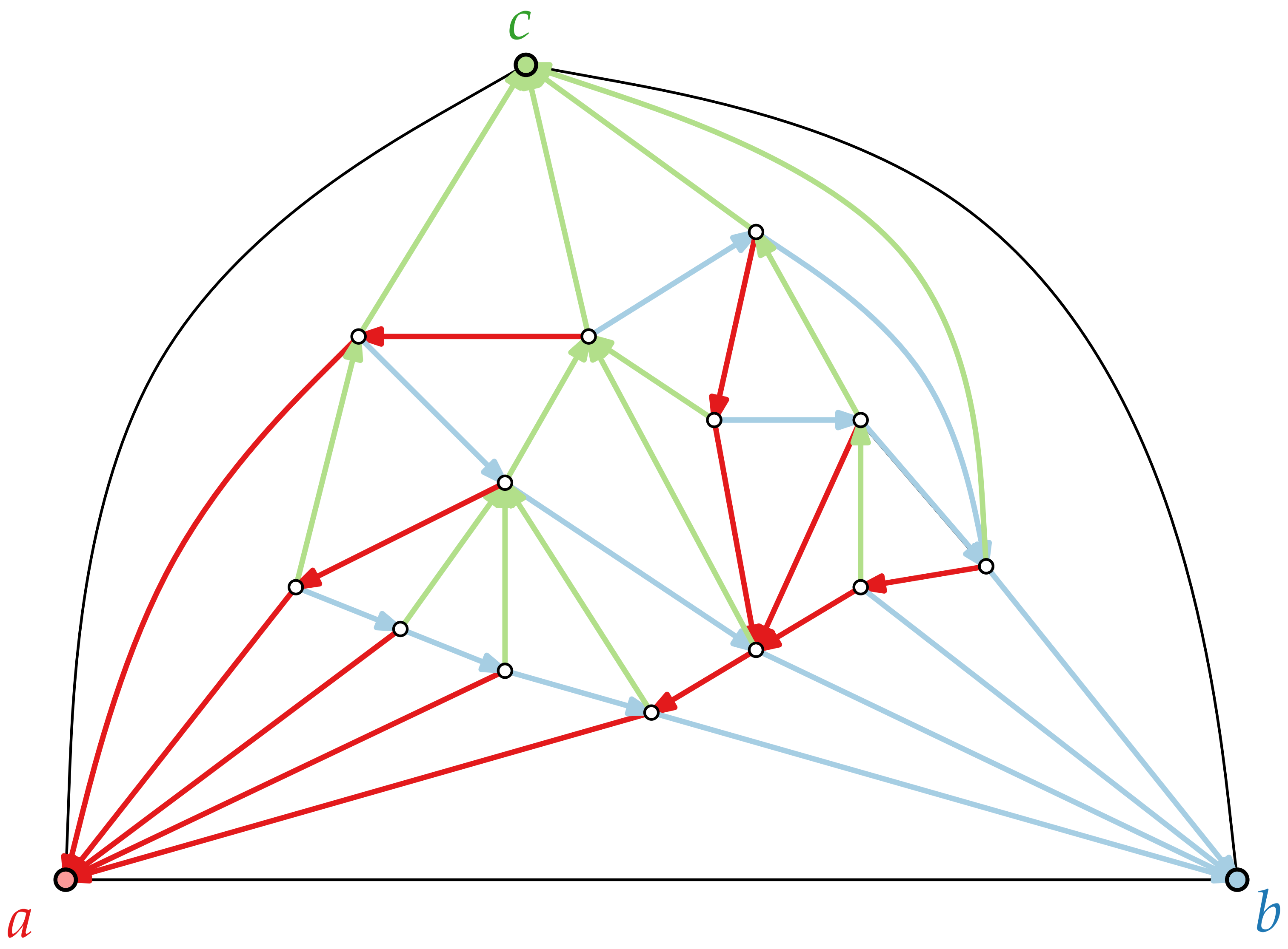

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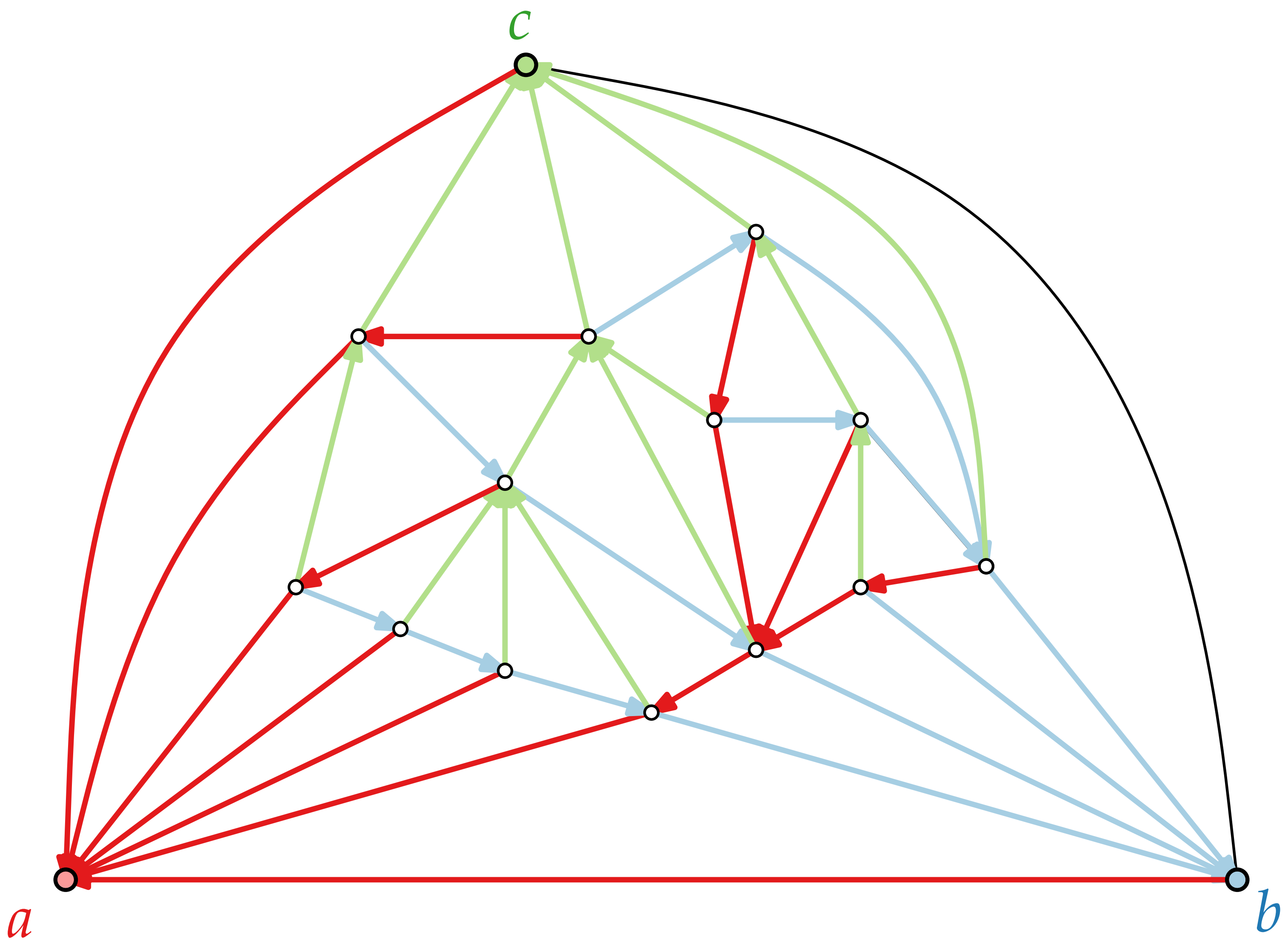

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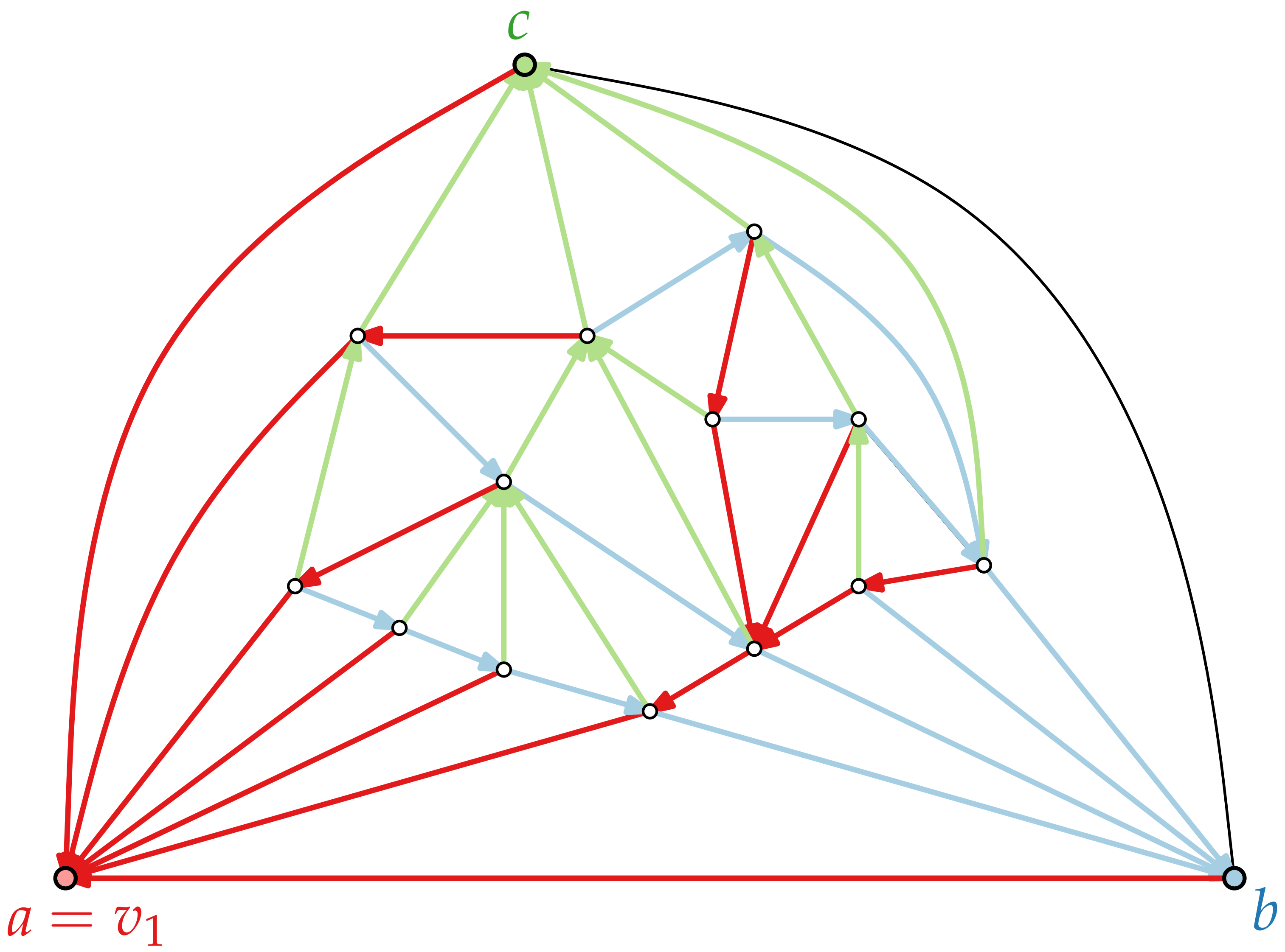

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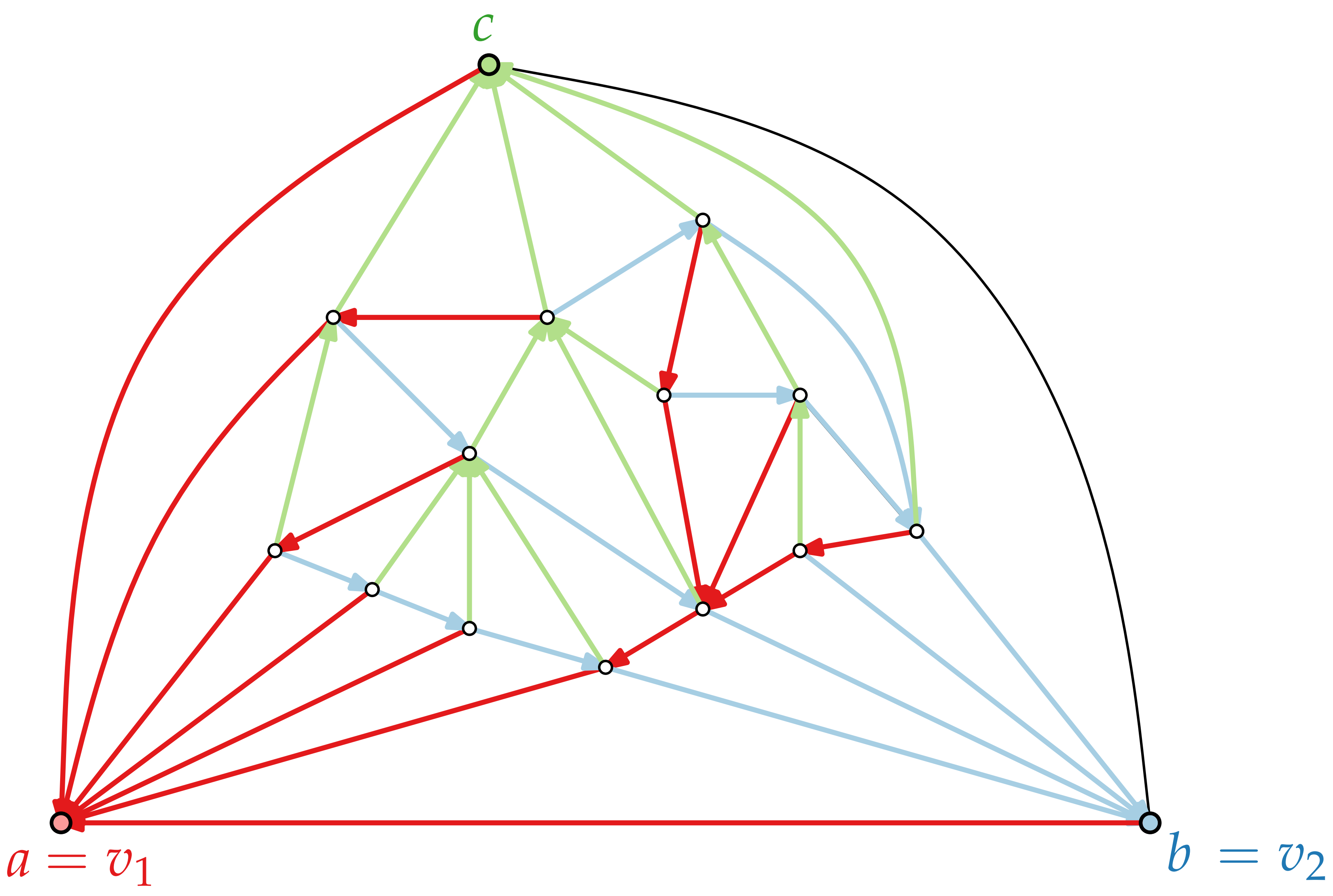

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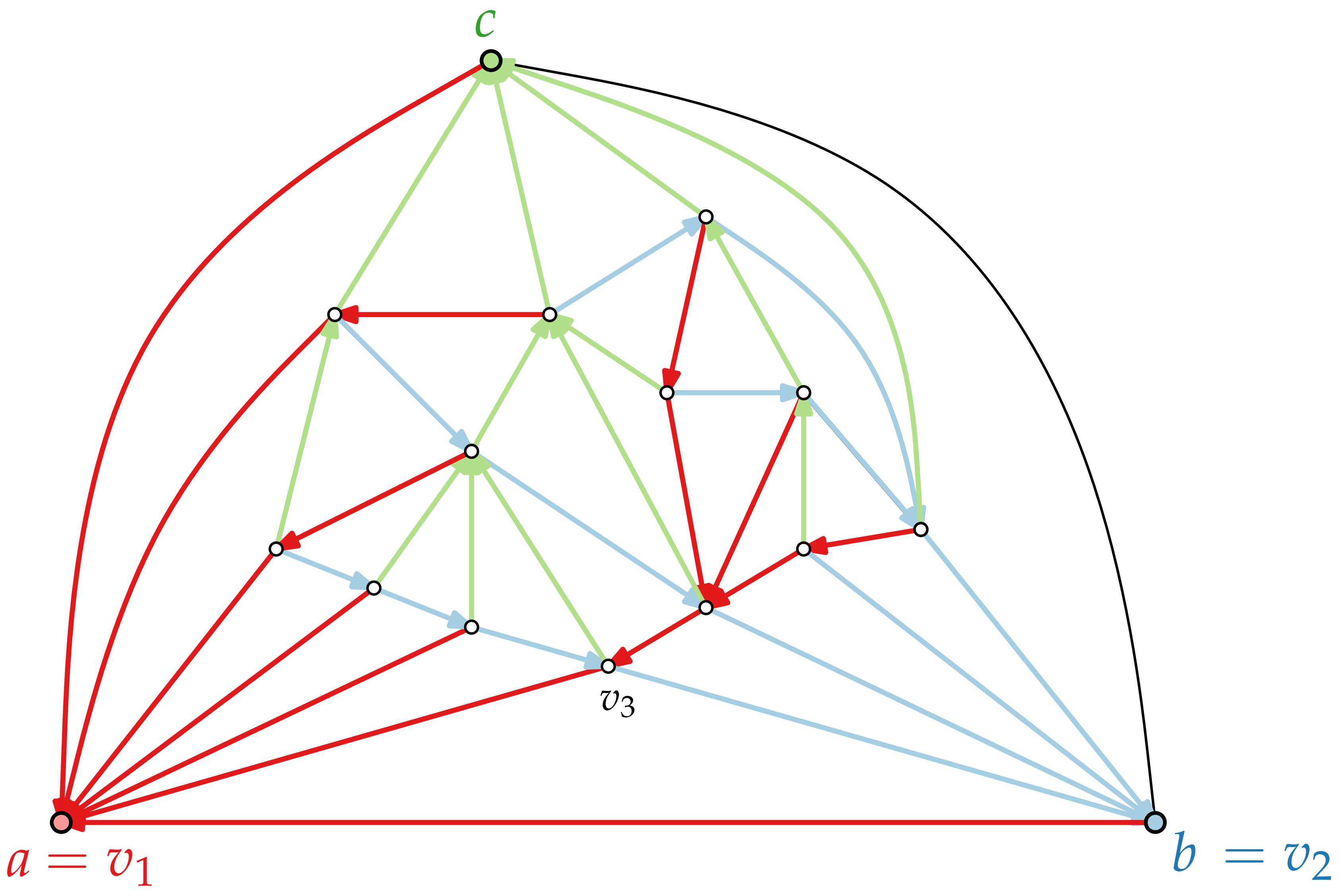

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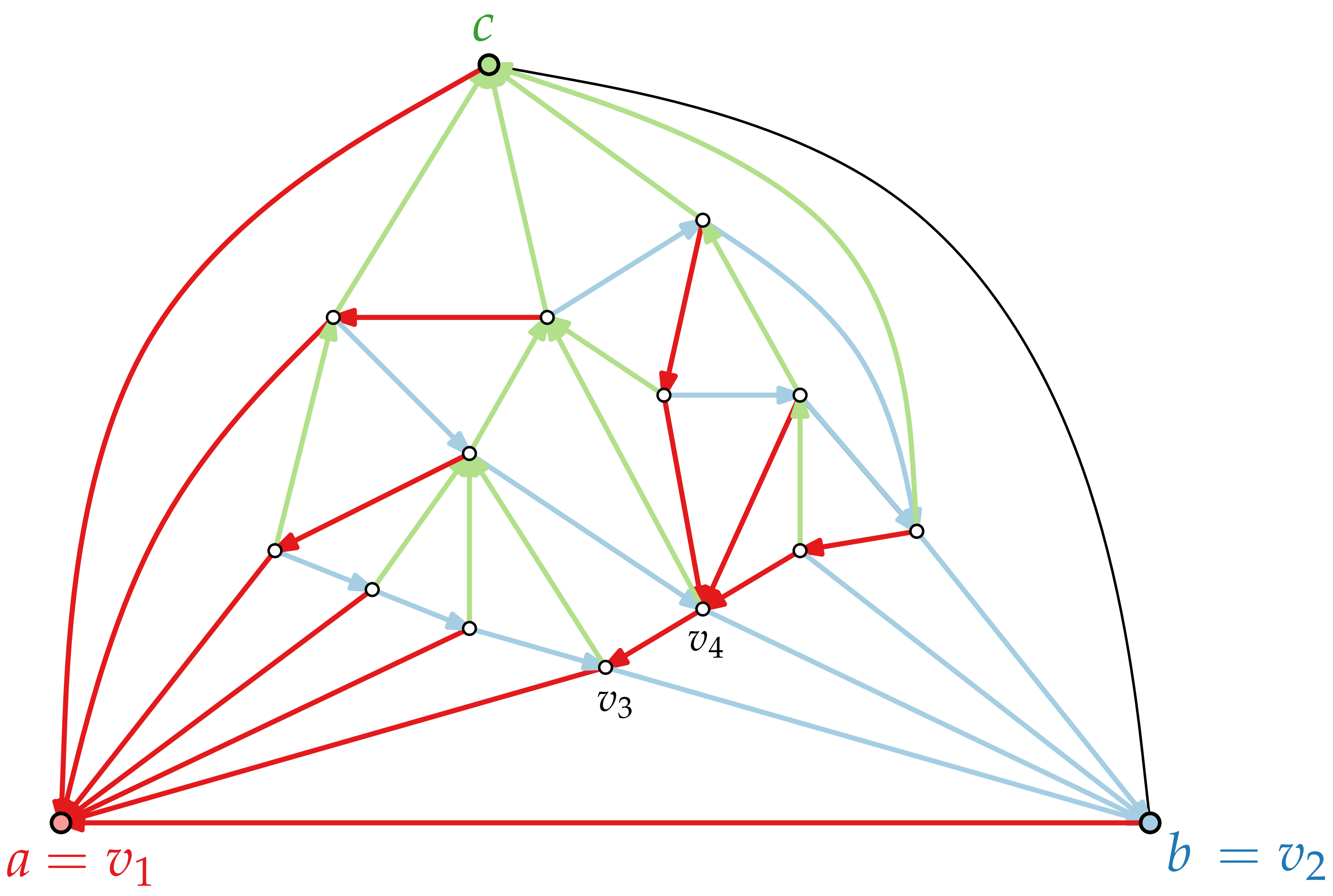

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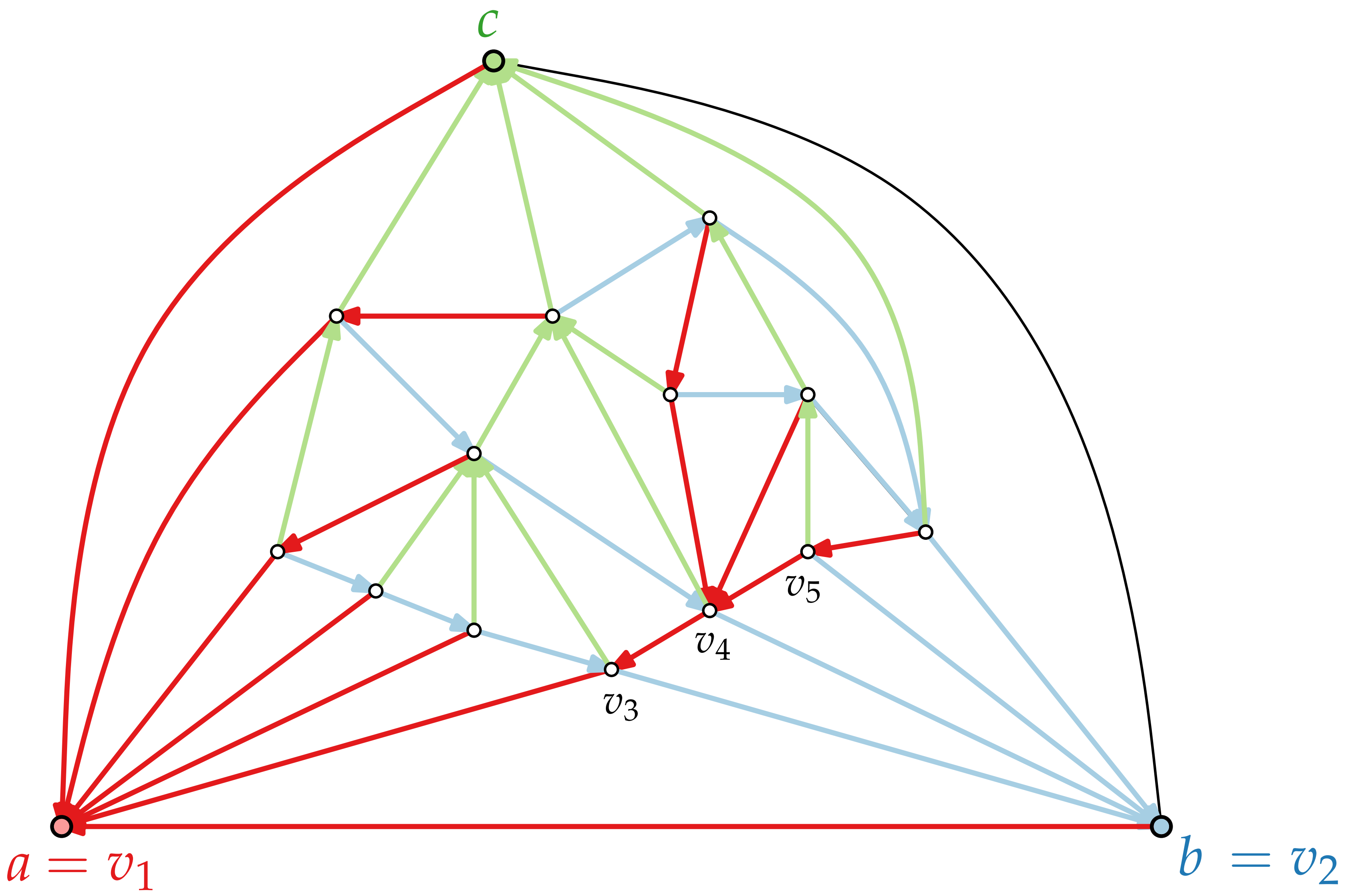

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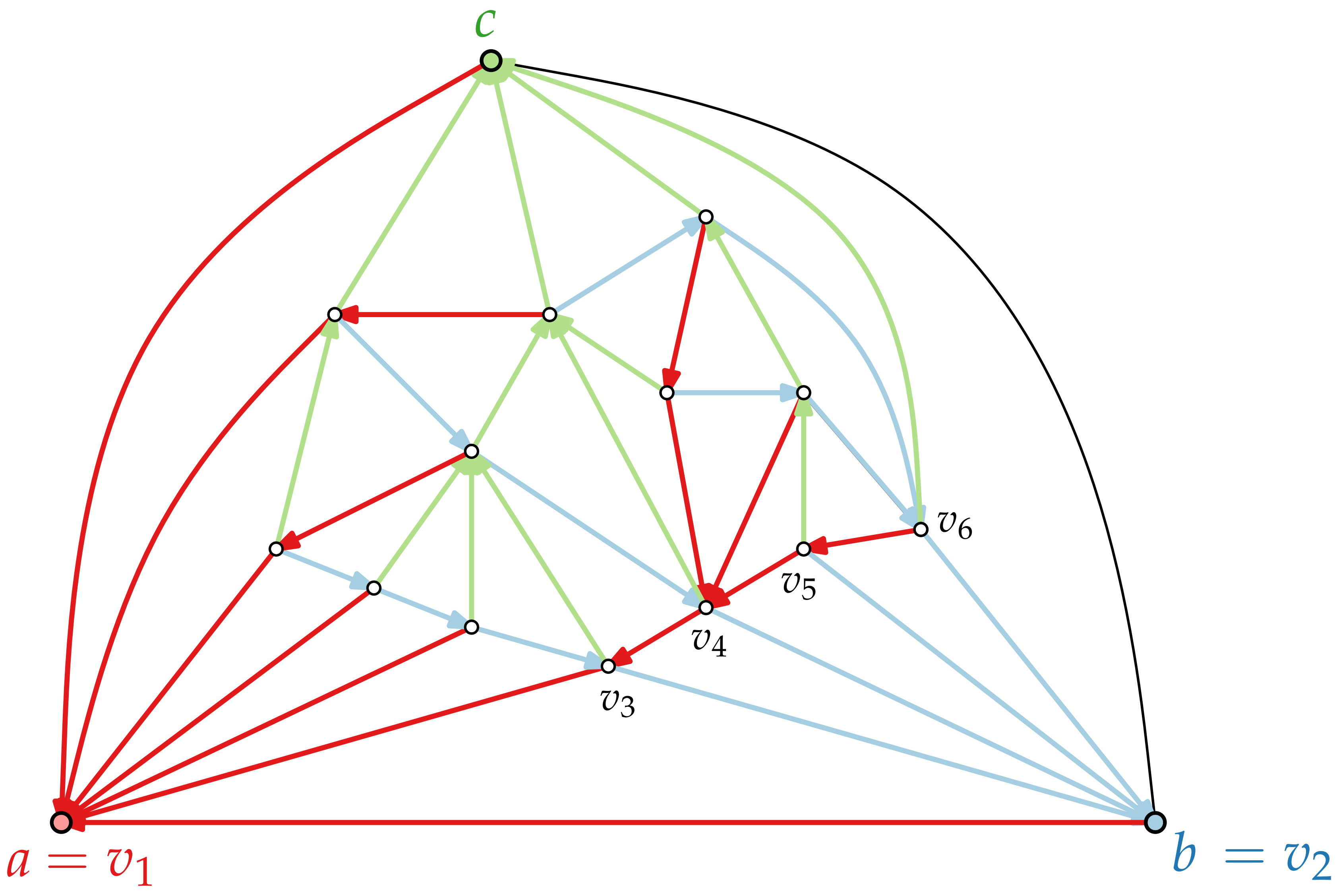

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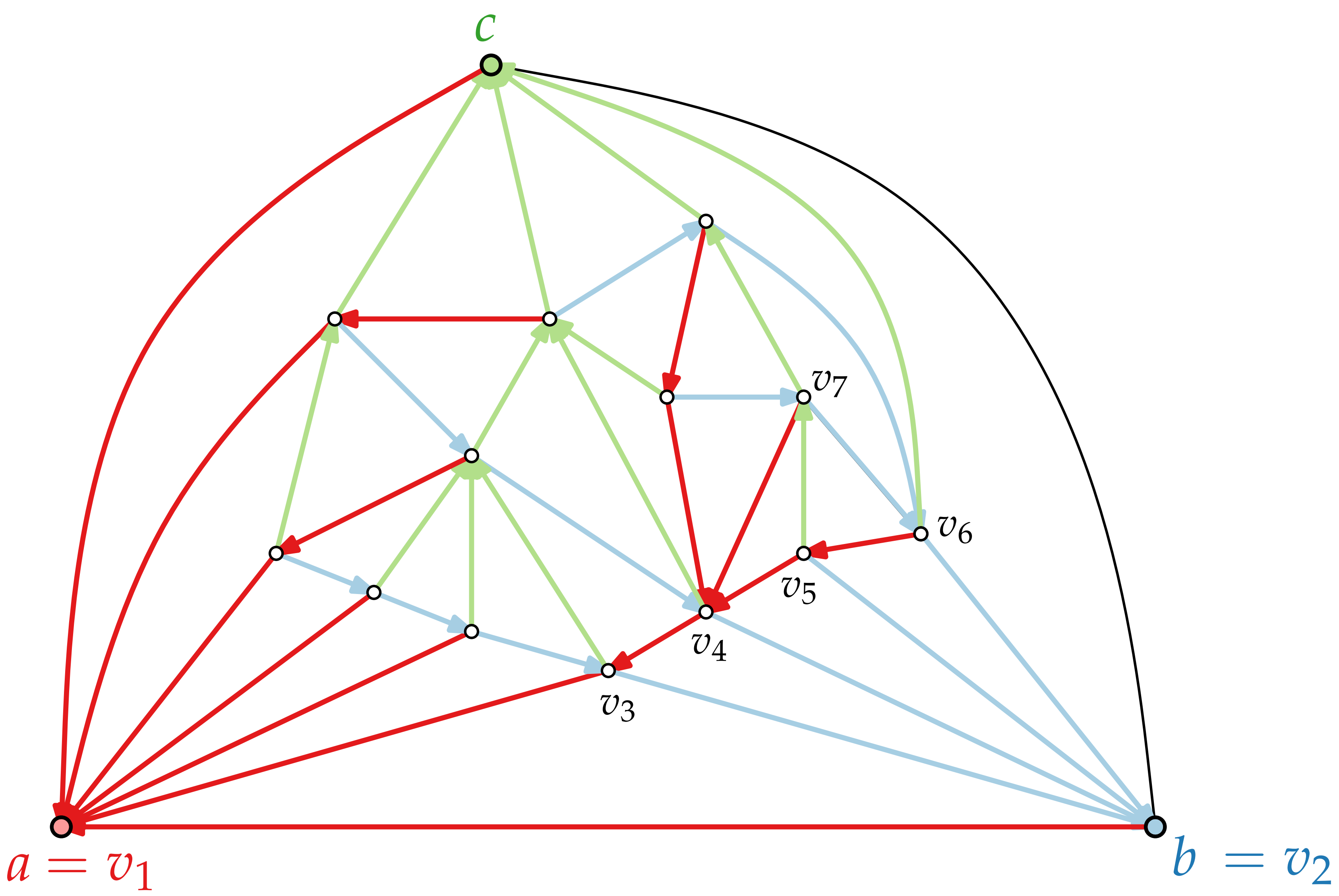

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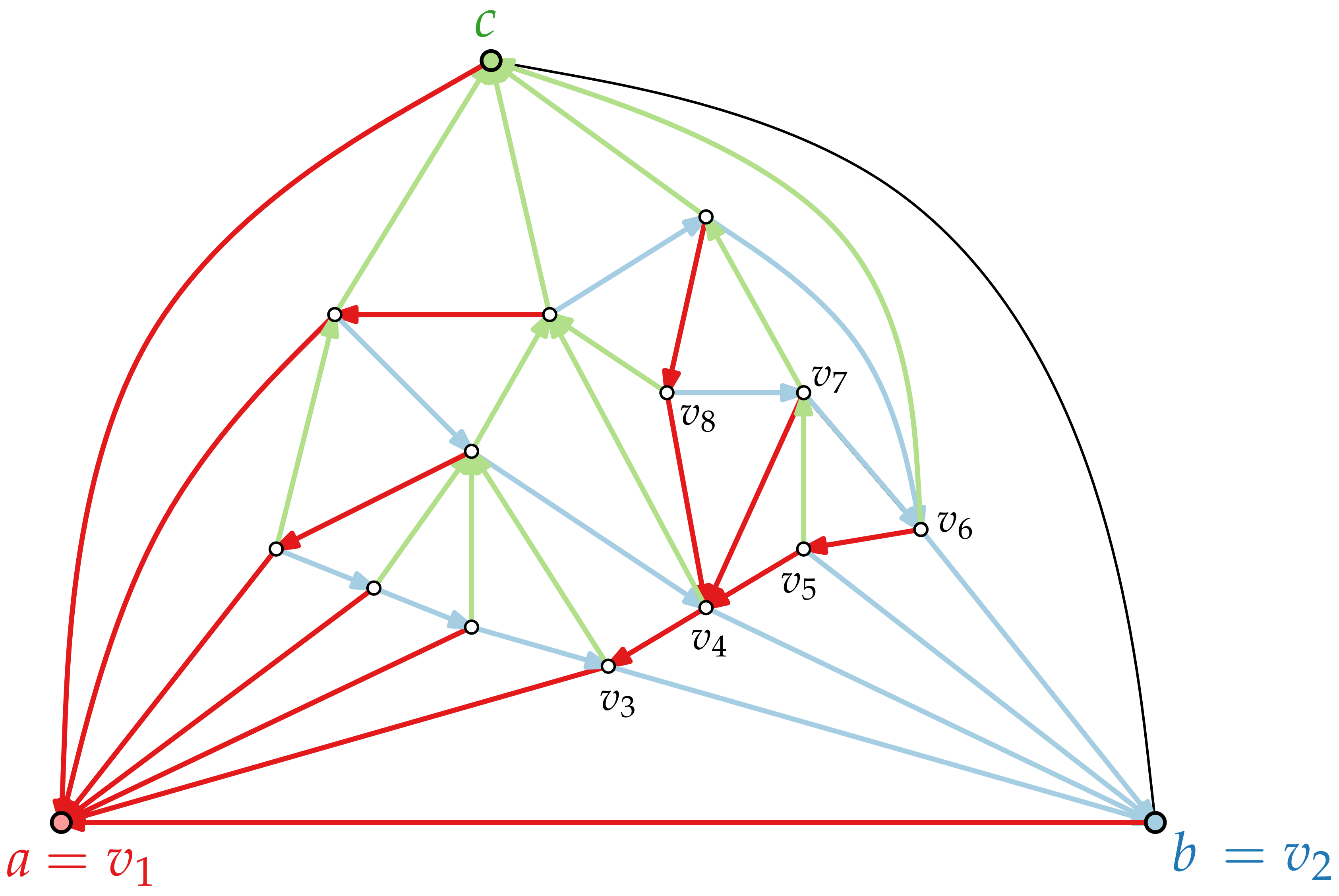

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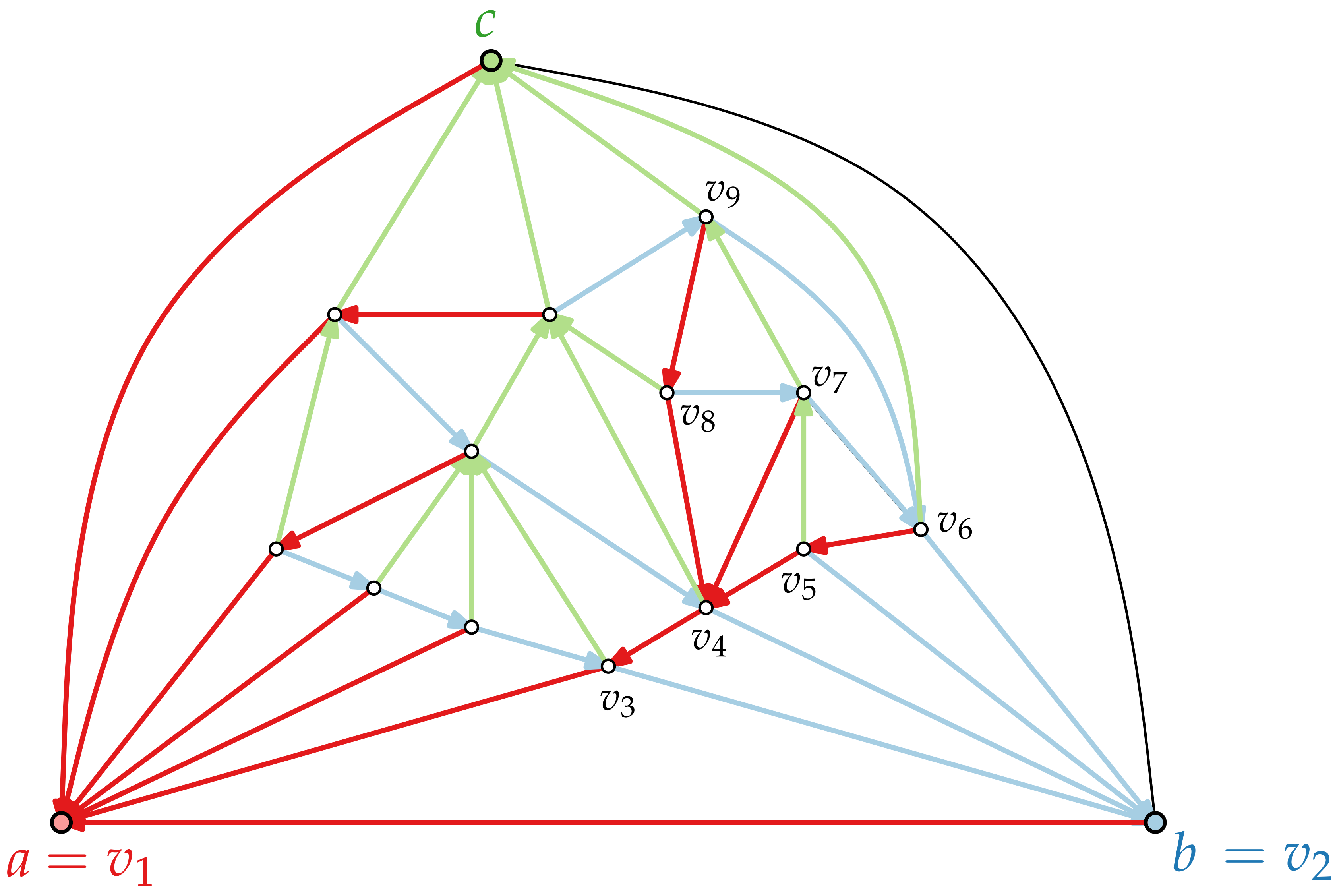

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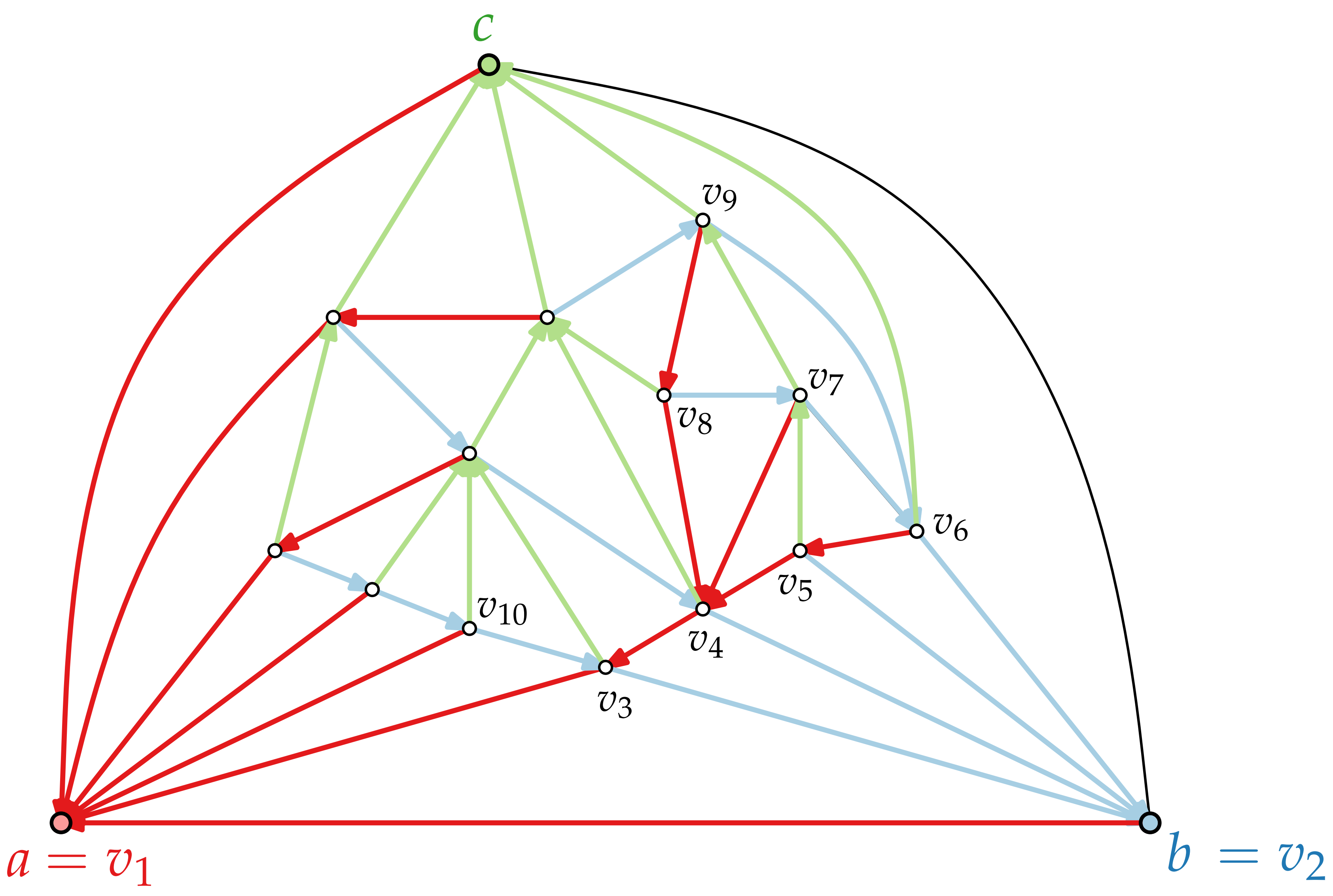

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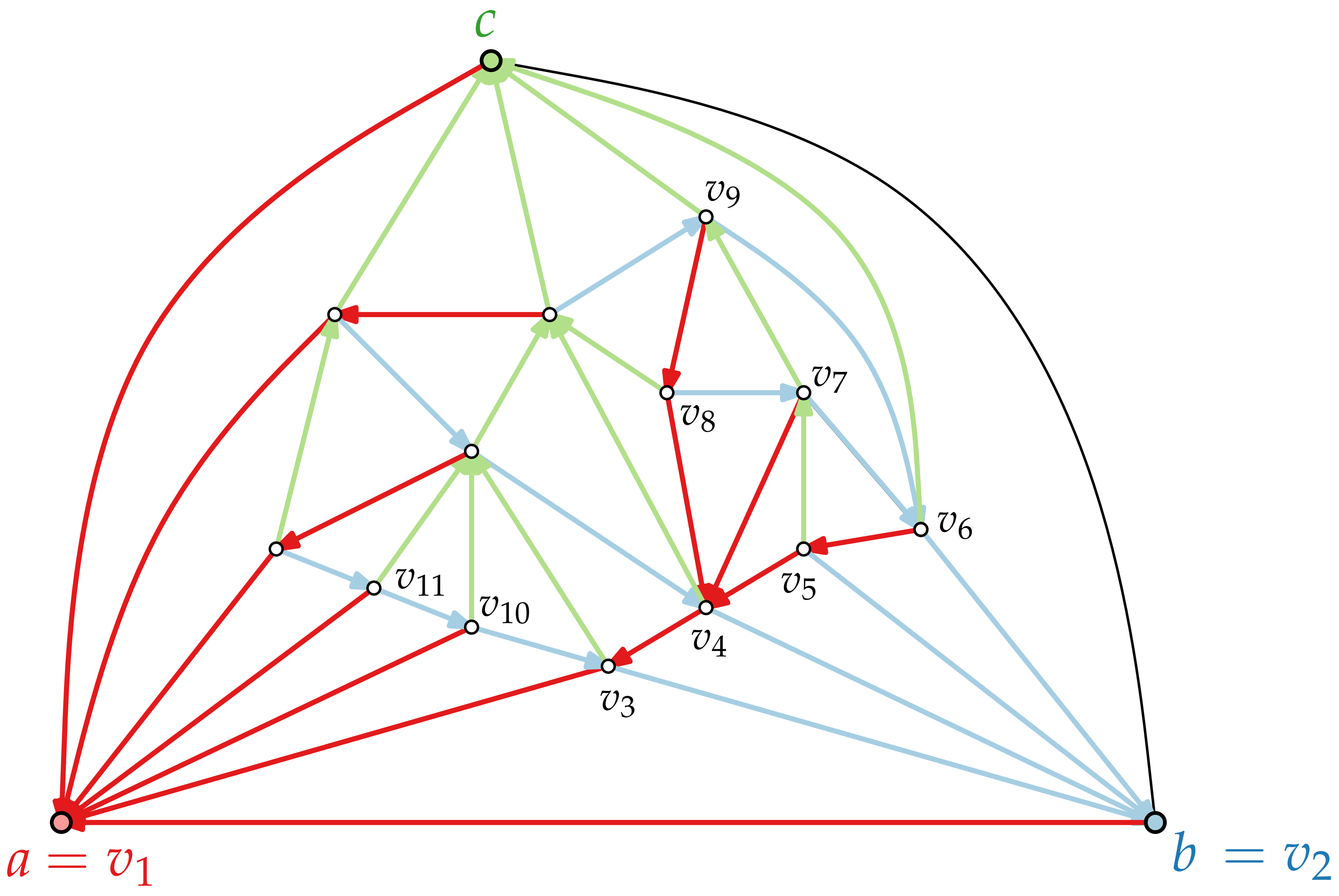

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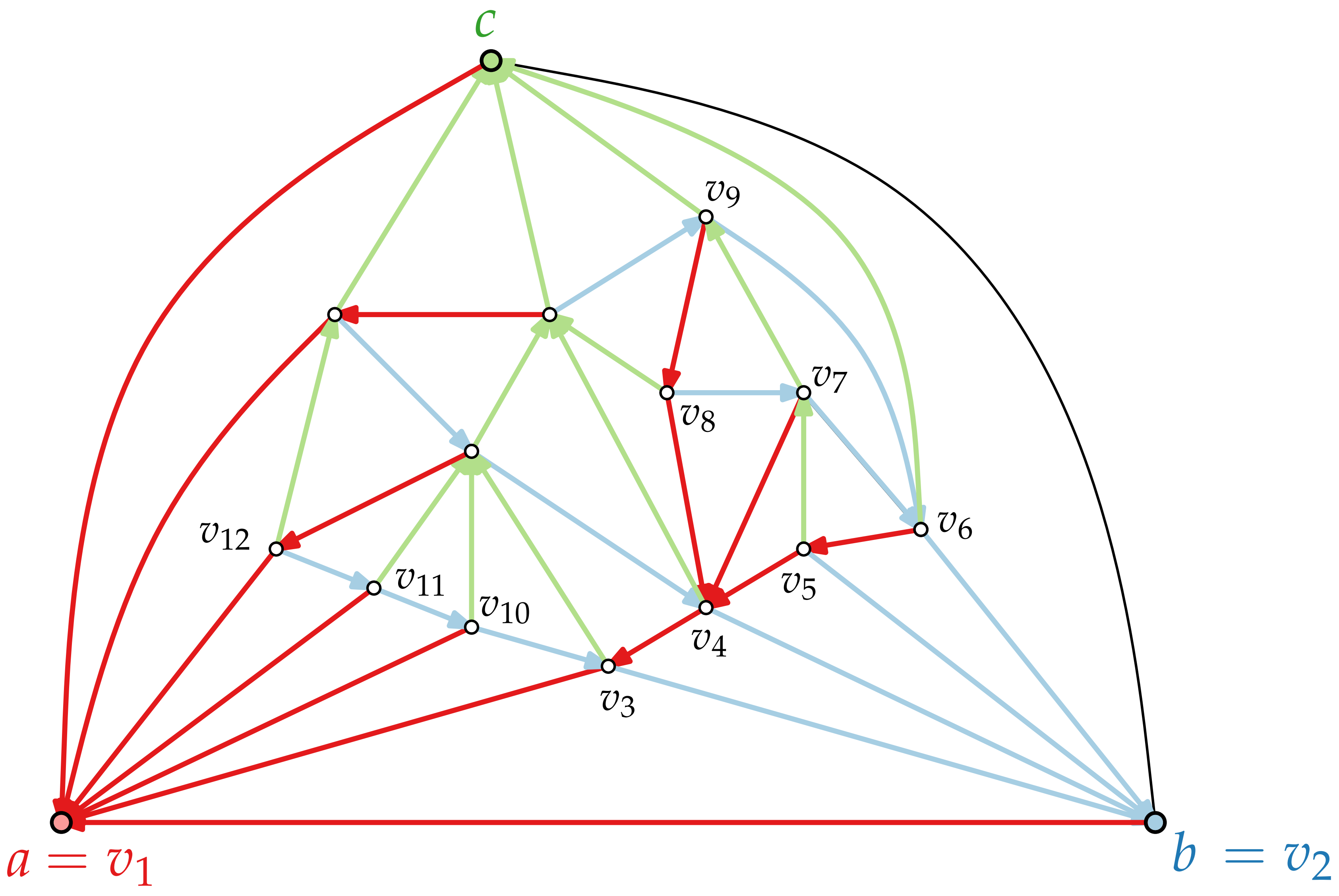

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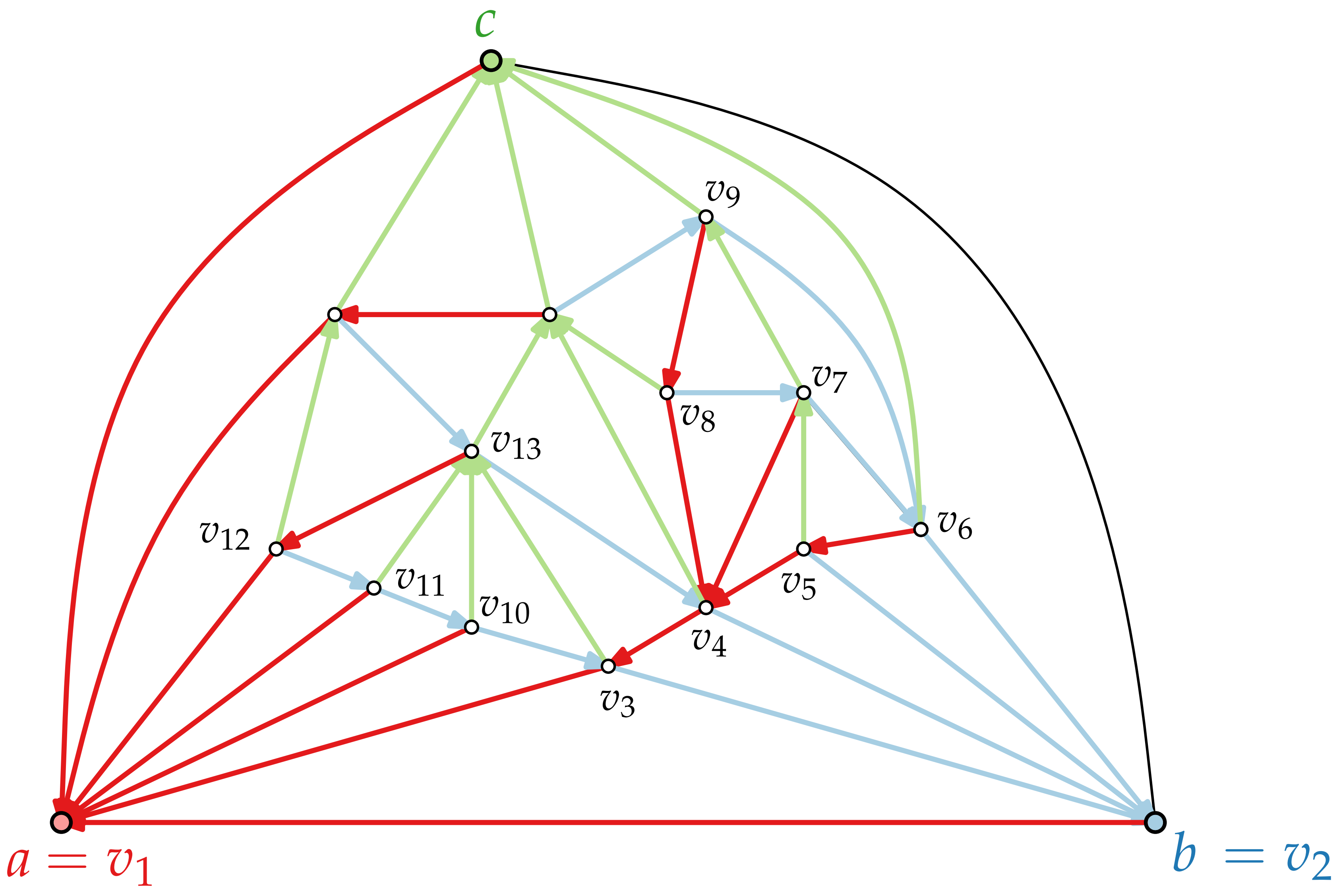
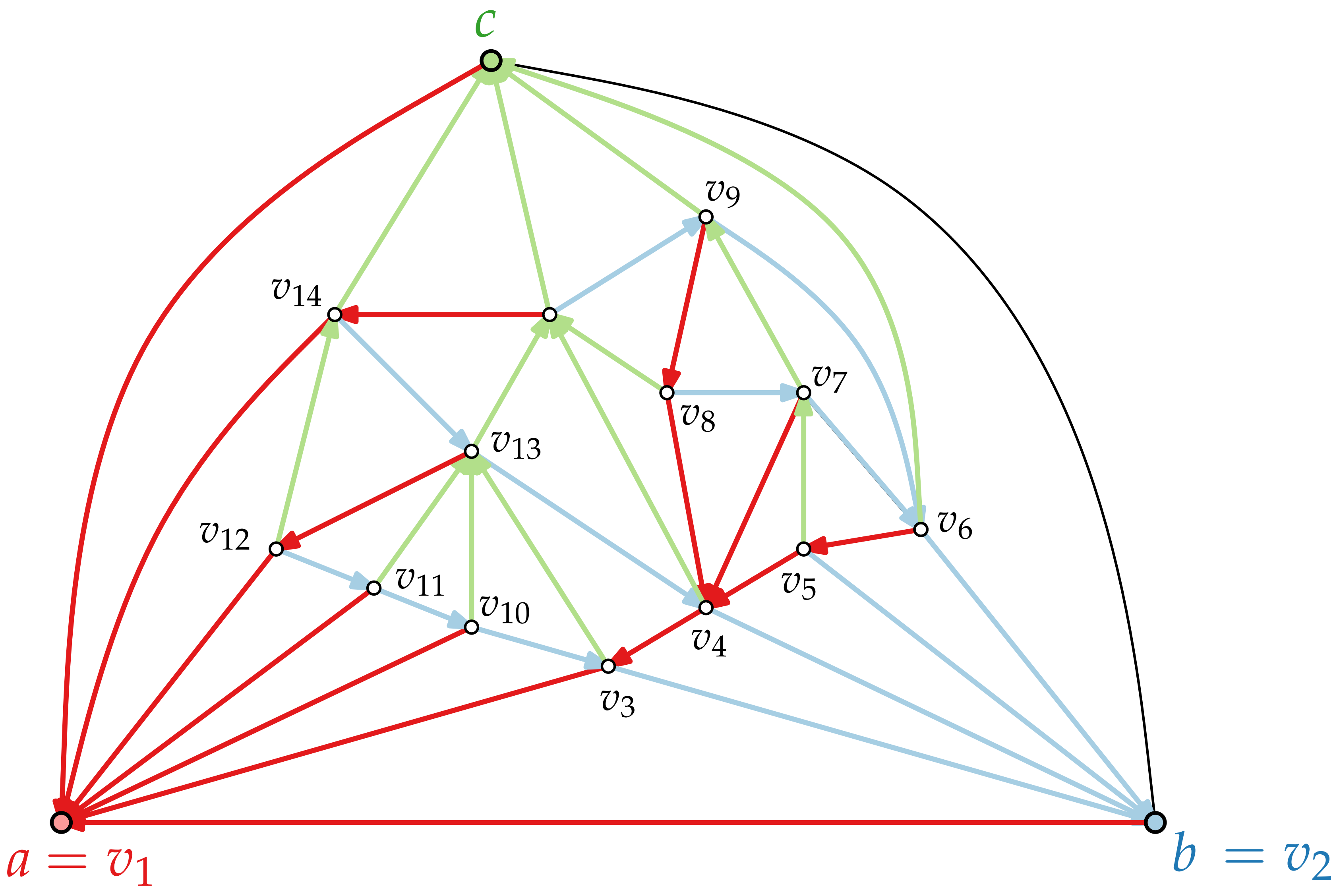
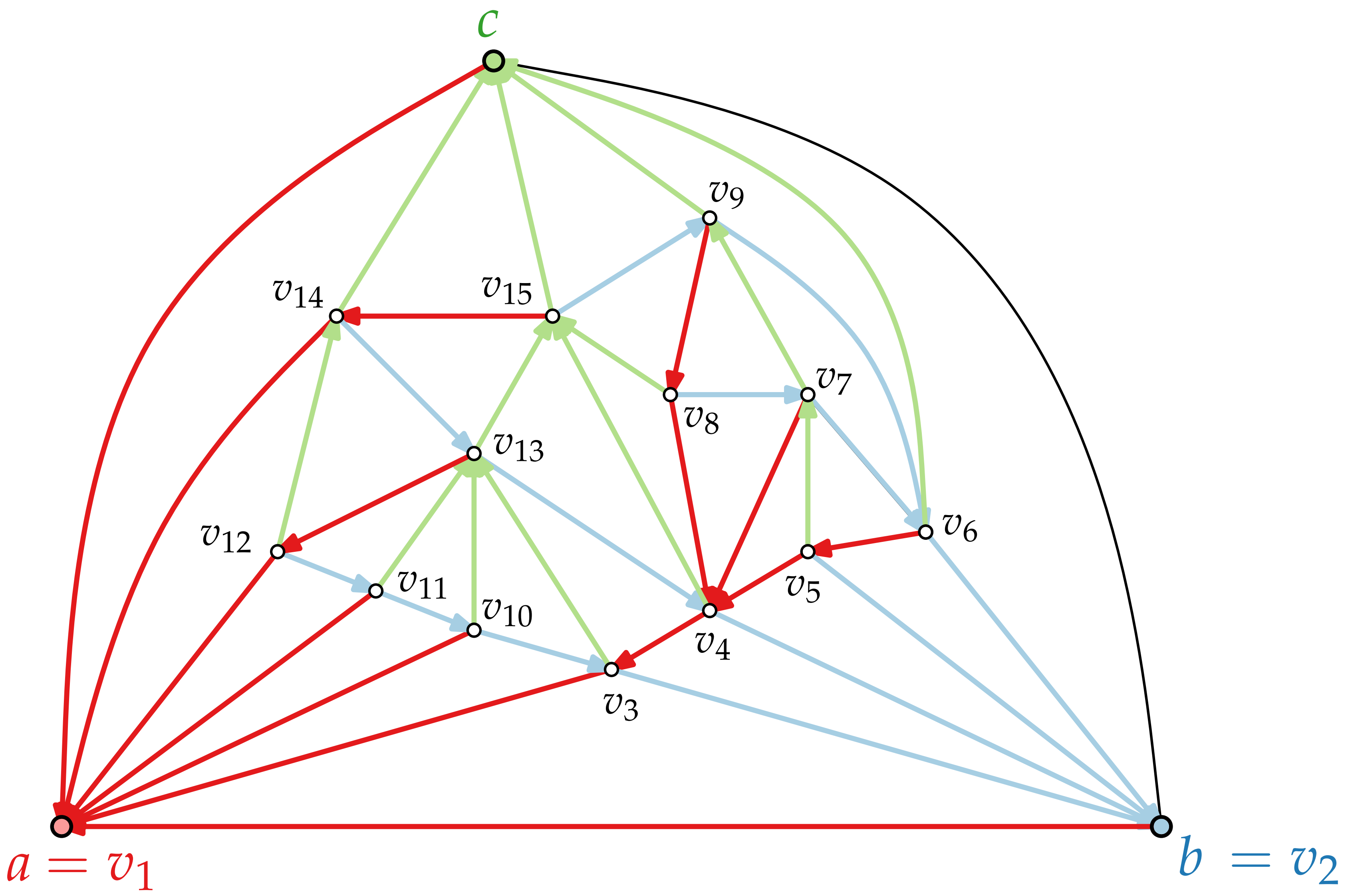


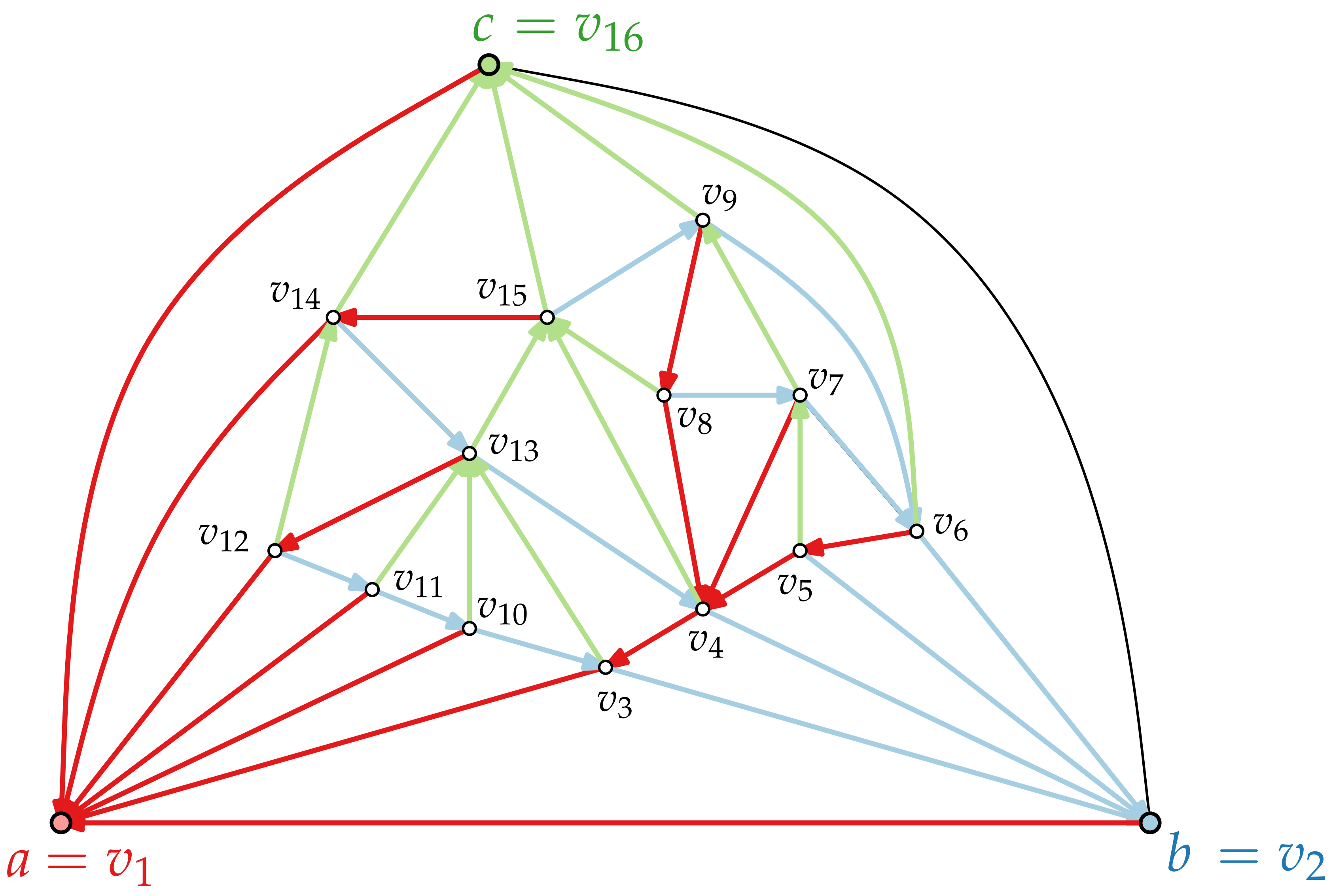
Schnyder Realizer → Canonical Order



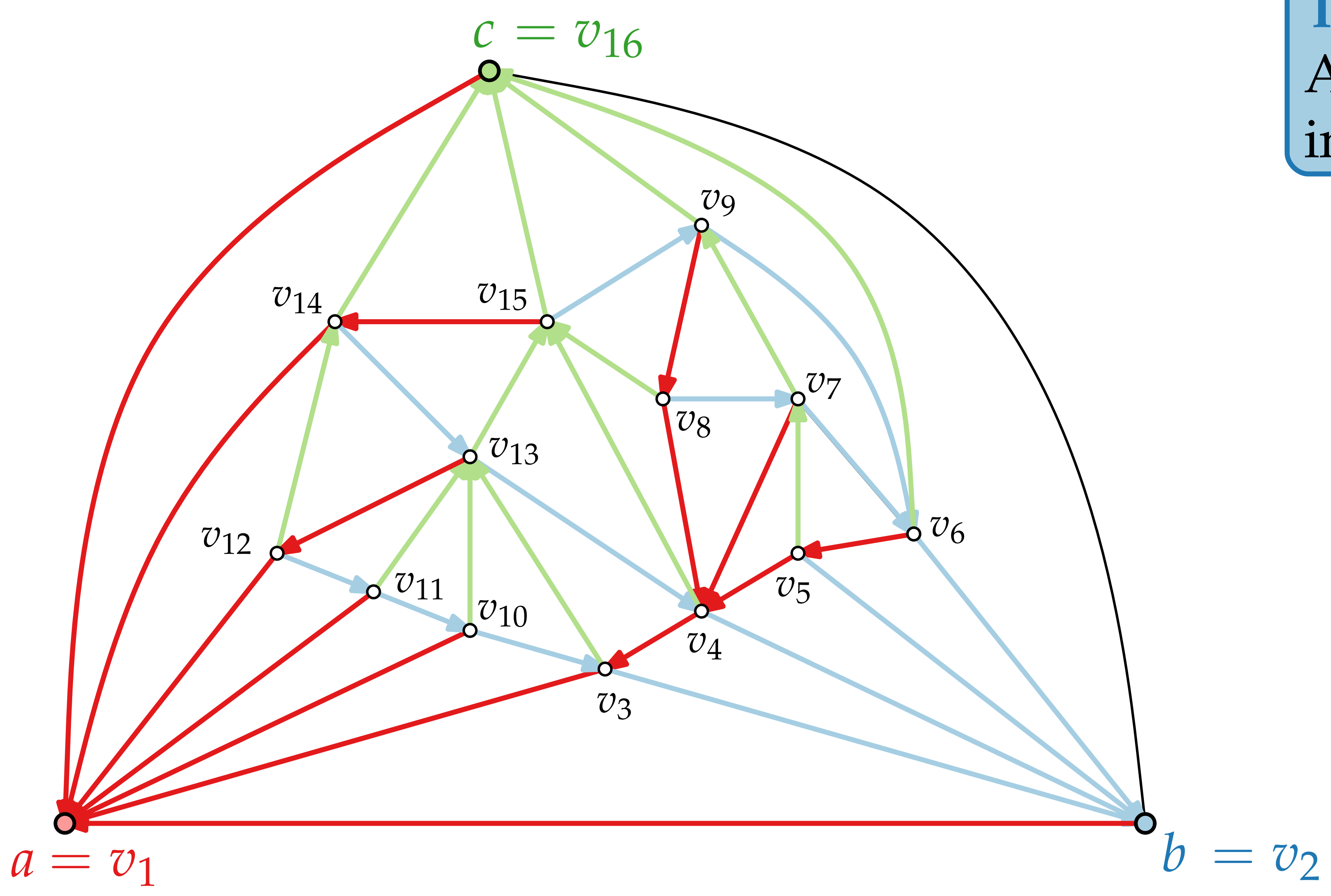
Schnyder Realizer → Canonical Order



Schnyder Realizer → Canonical Order

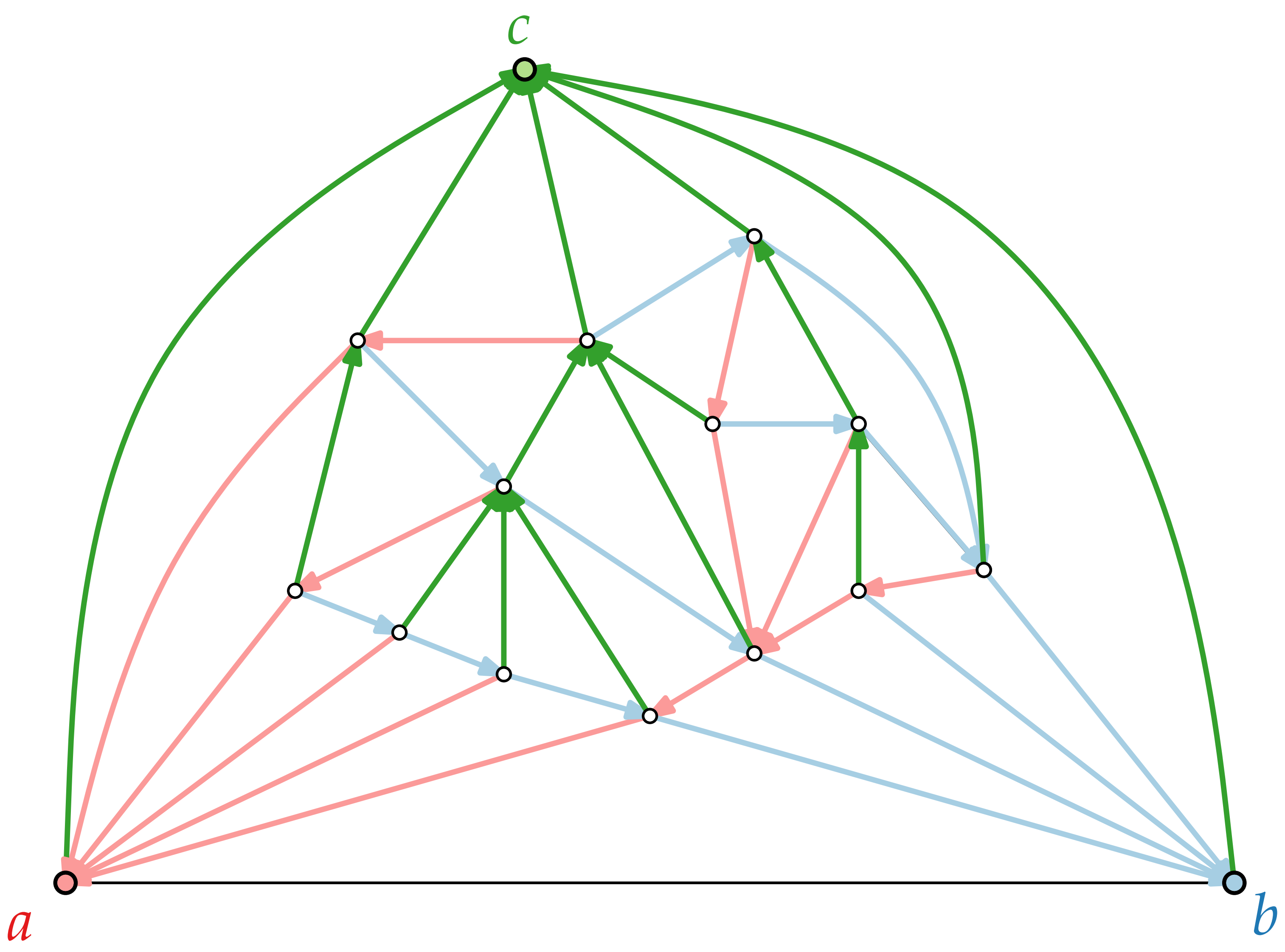


Schnyder Realizer → Canonical Order



Theorem.
A ccw pre-order traversal on T_i induces a canonical order.

Schnyder Realizer → Canonical Order



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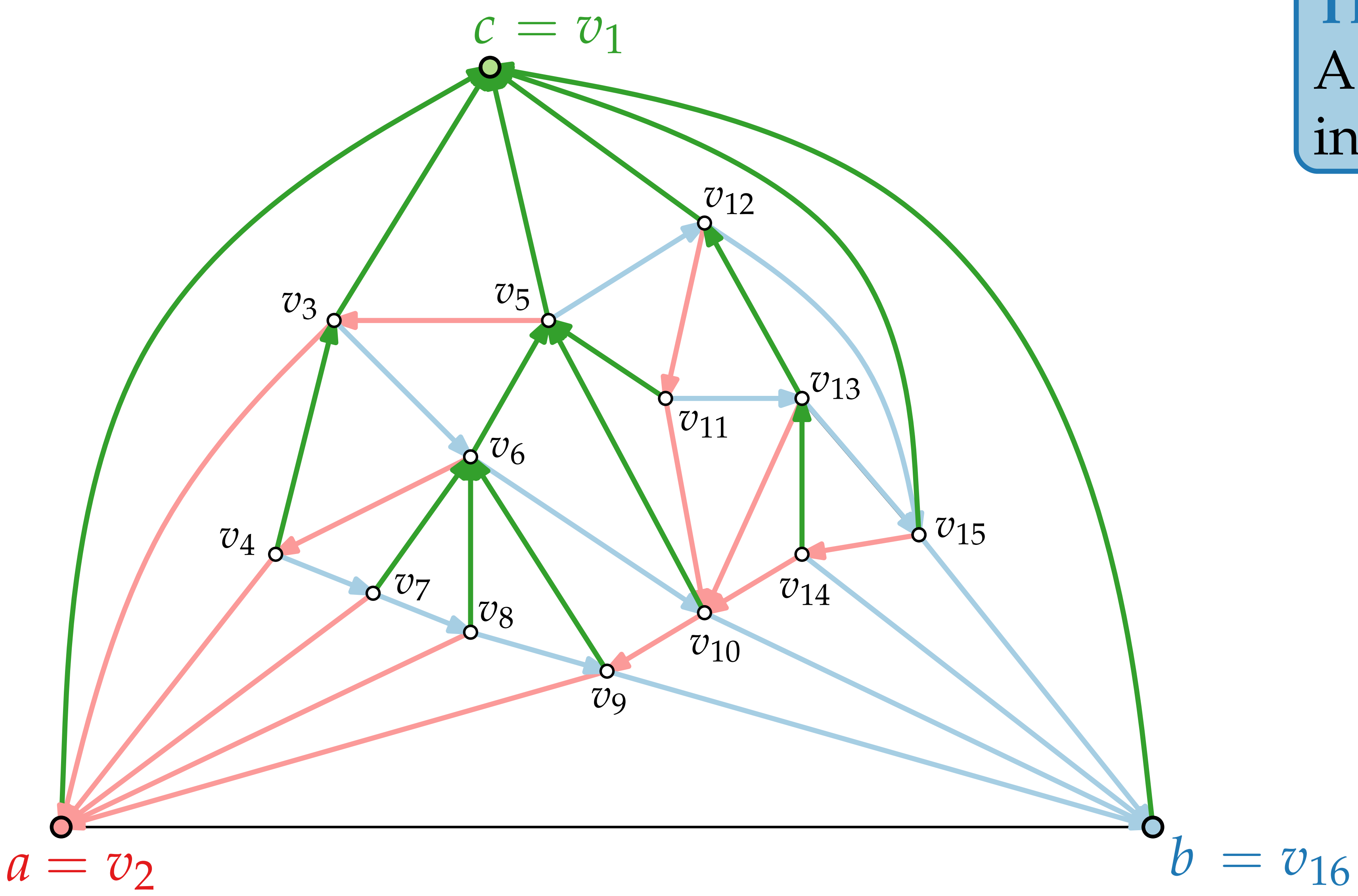

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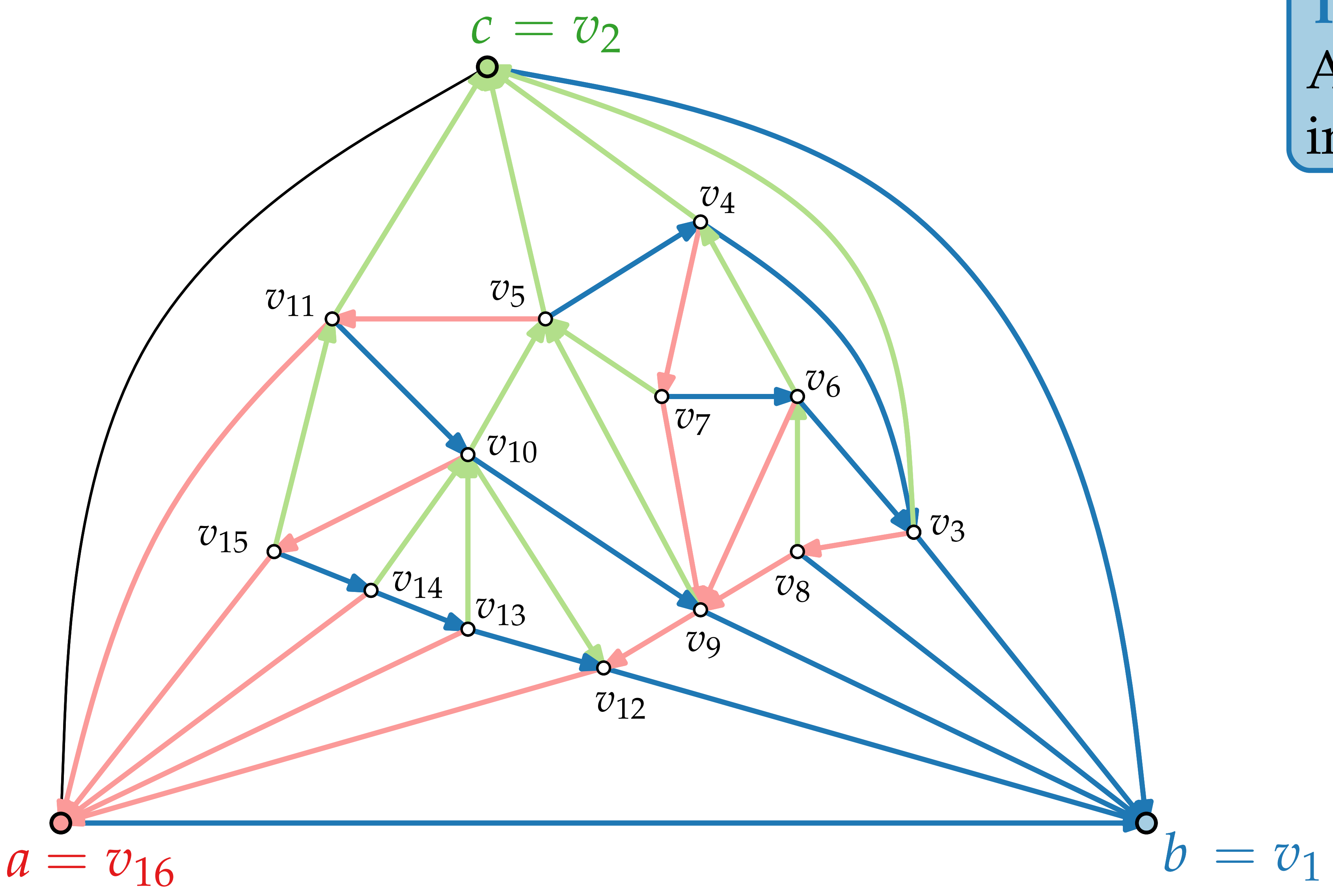
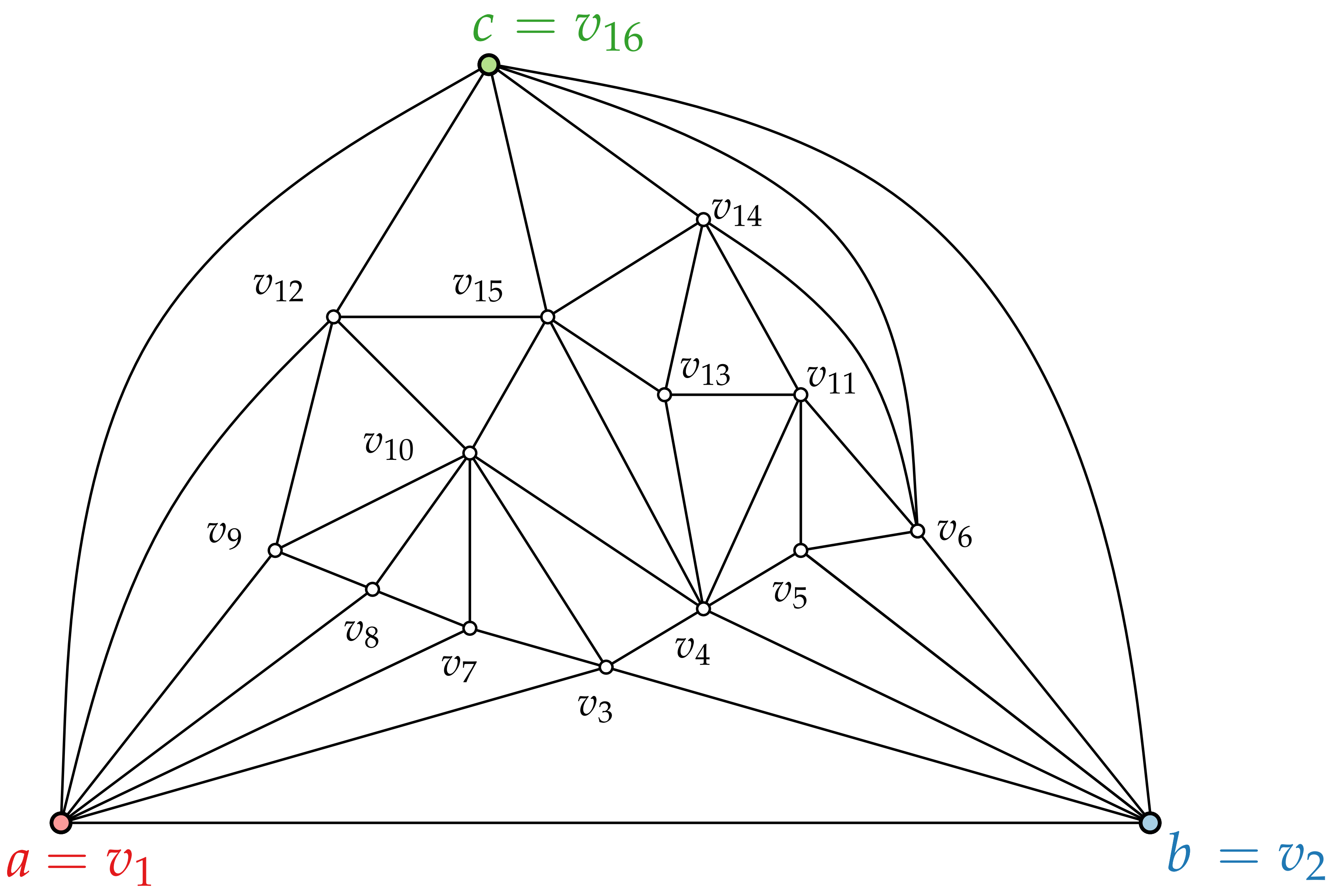
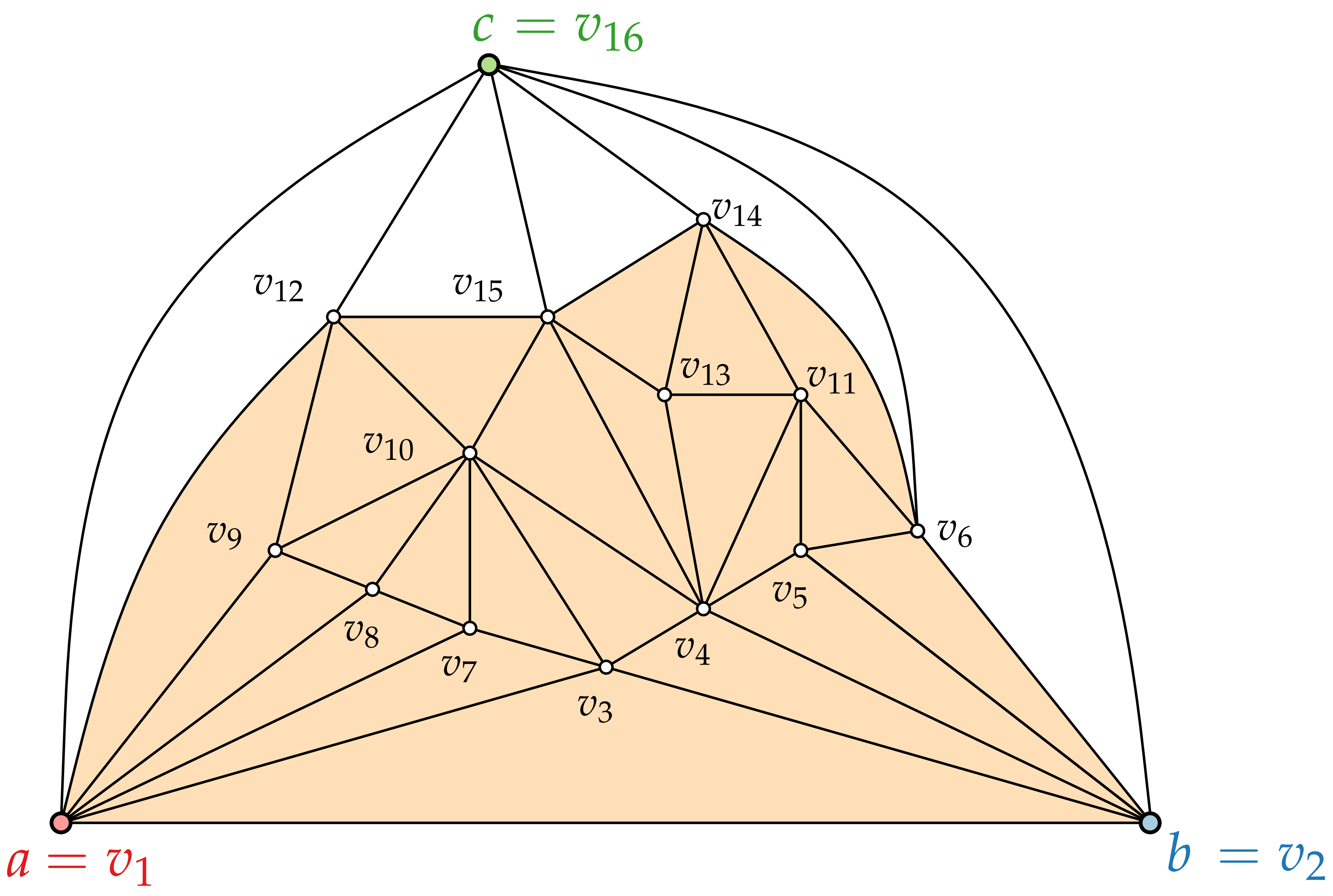


Theorem.
A ccw pre-order traversal on T_i induces a canonical order.

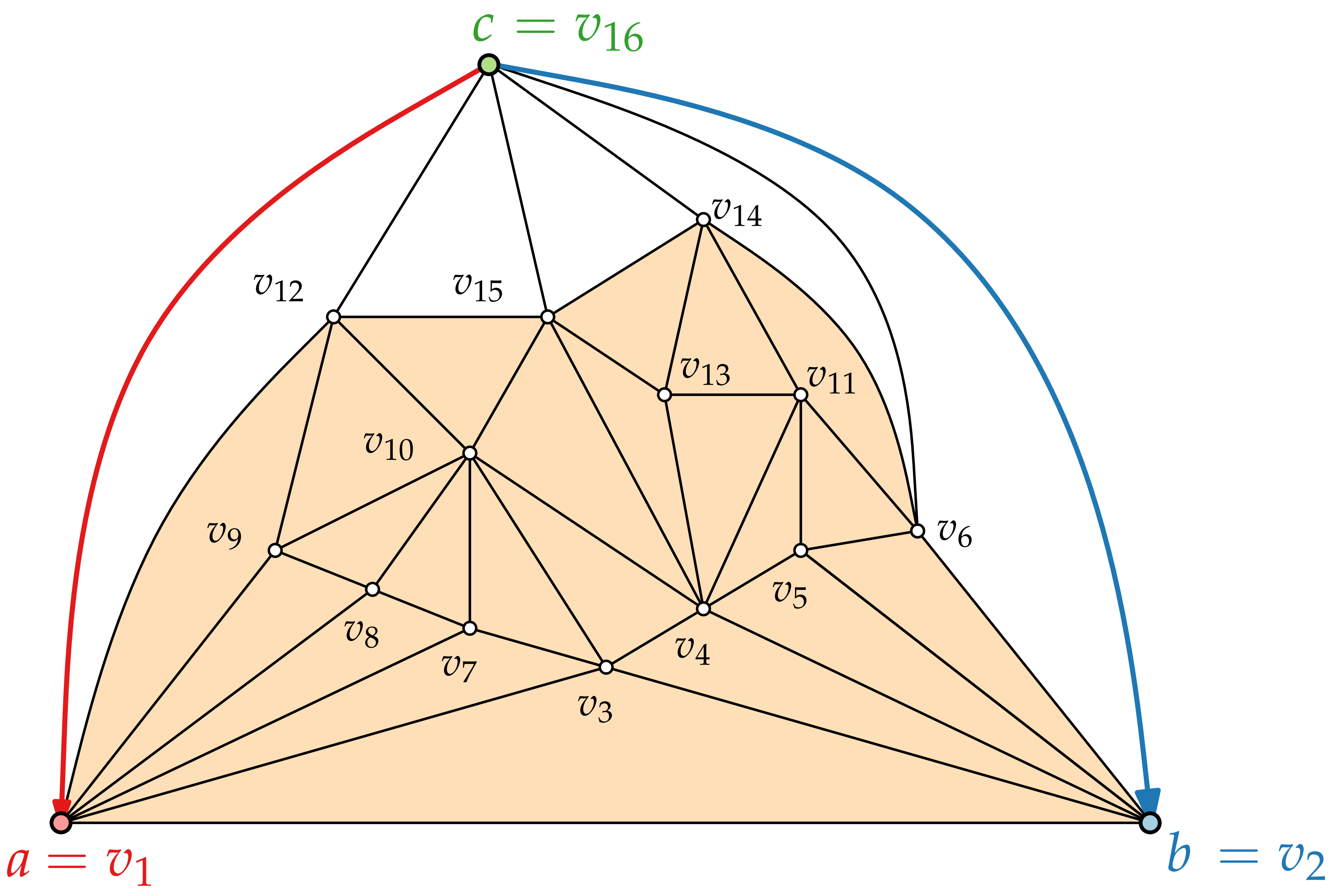
Canonical Order → Schnyder Realizer



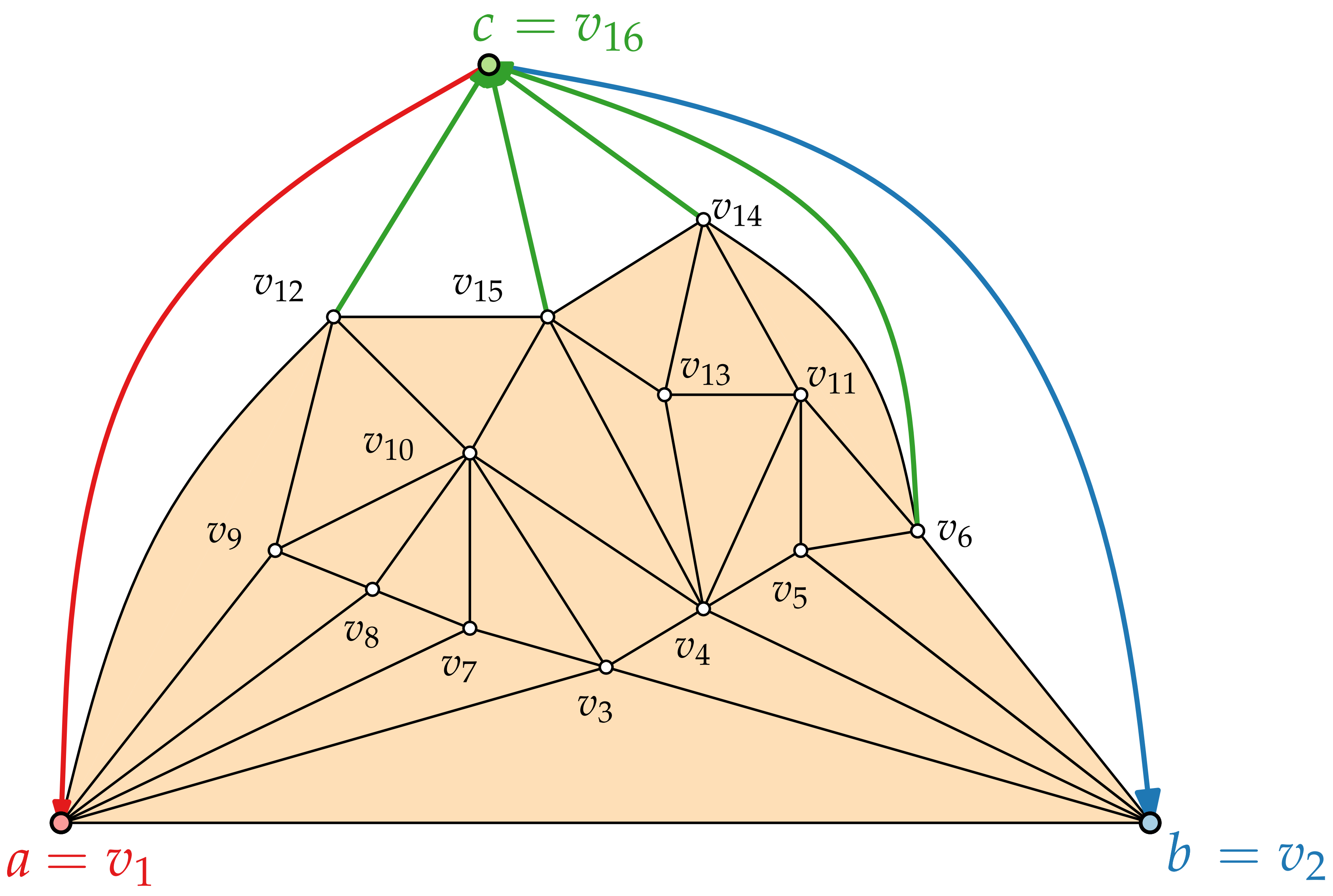
Canonical Order → Schnyder Realizer



Canonical Order → Schnyder Realizer



Canonical Order → Schnyder Realizer



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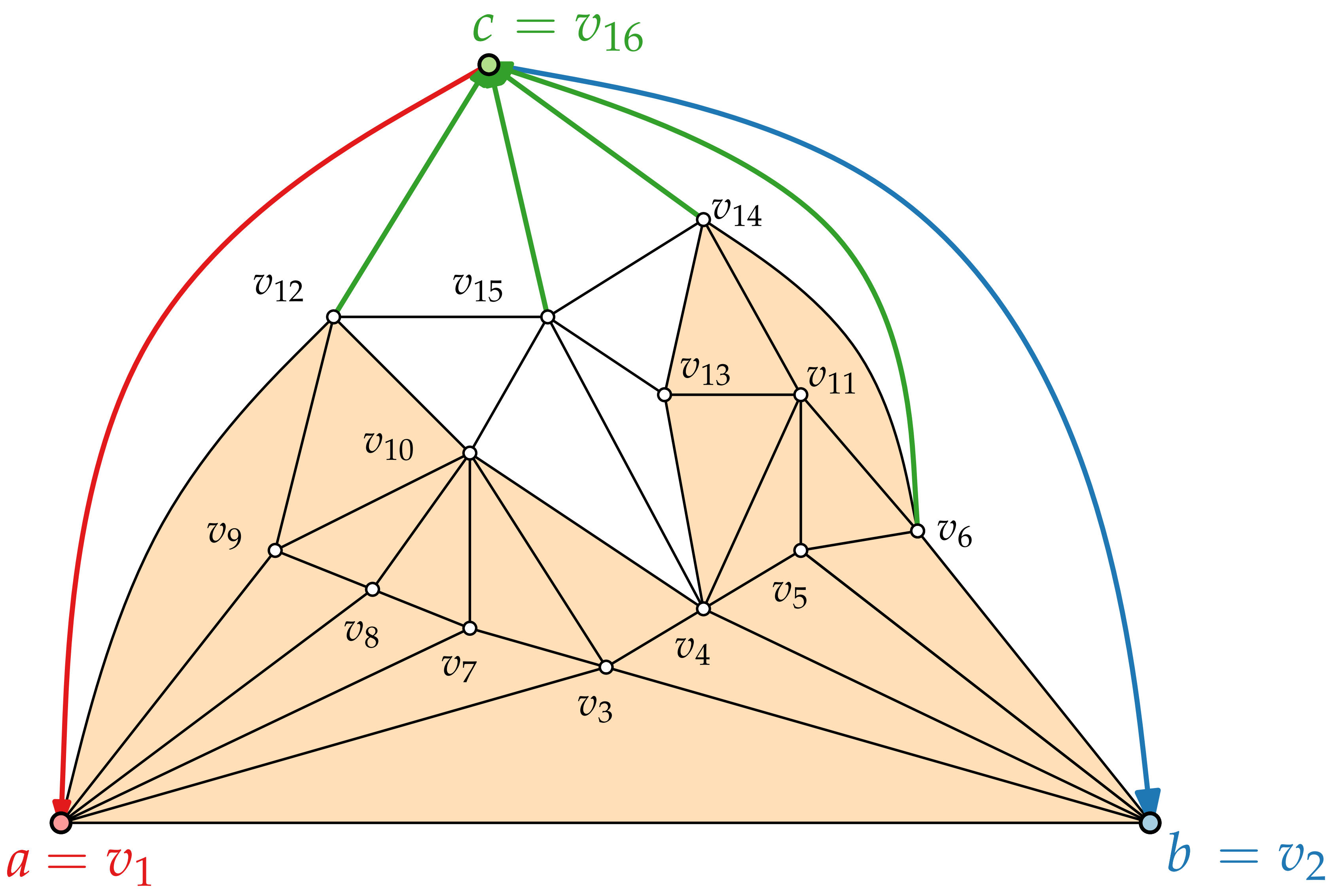

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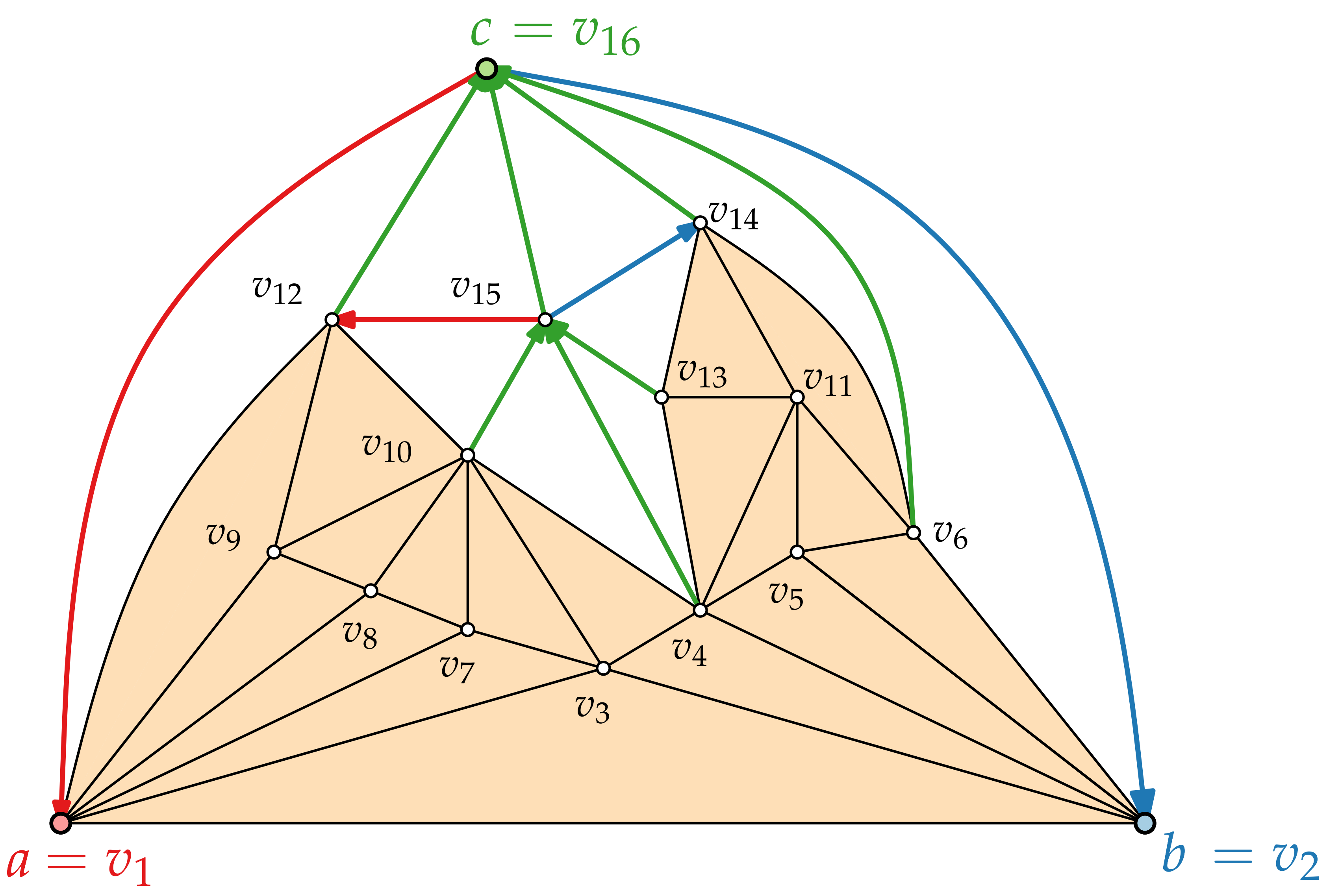
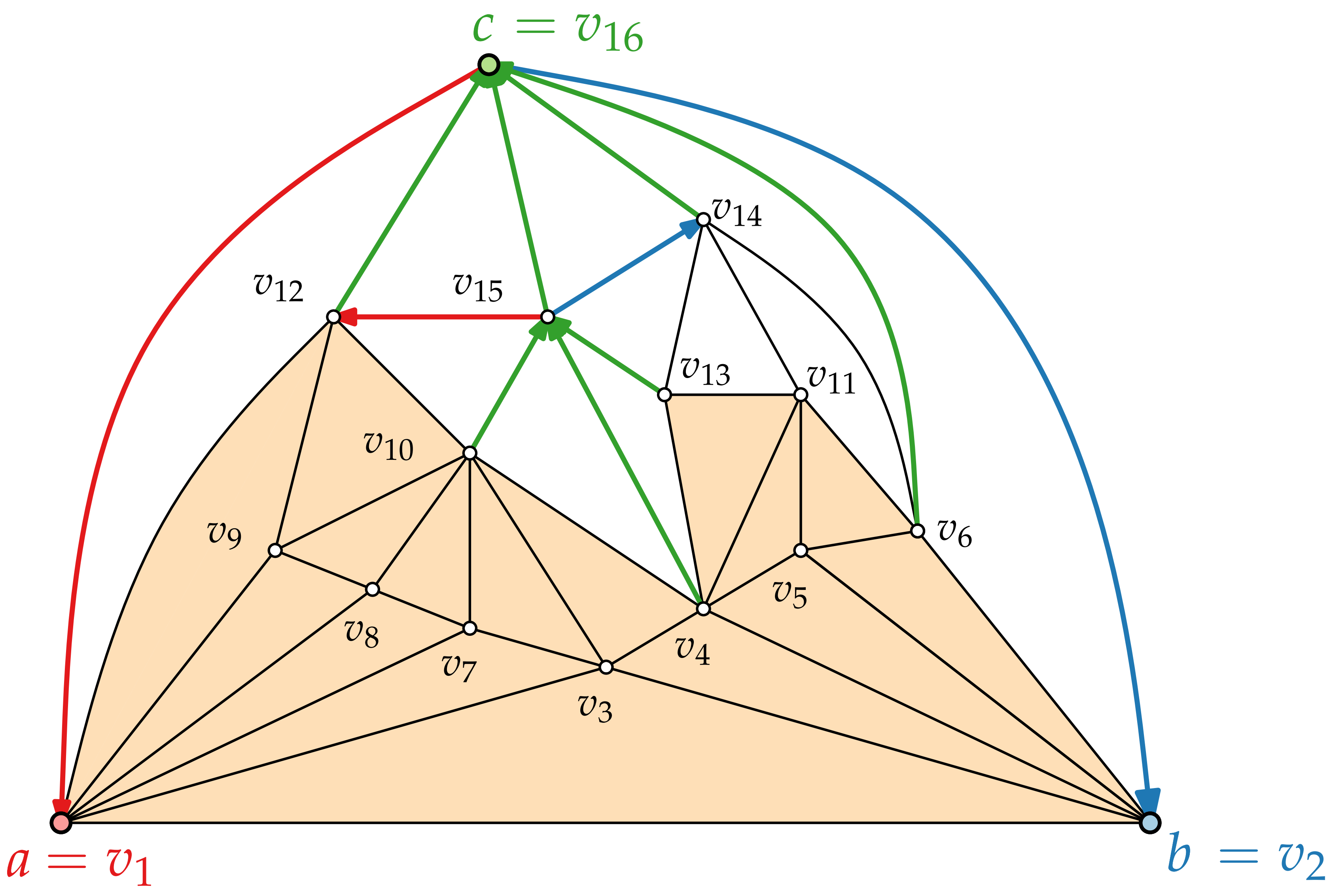


Canonical Order → Schnyder Realizer



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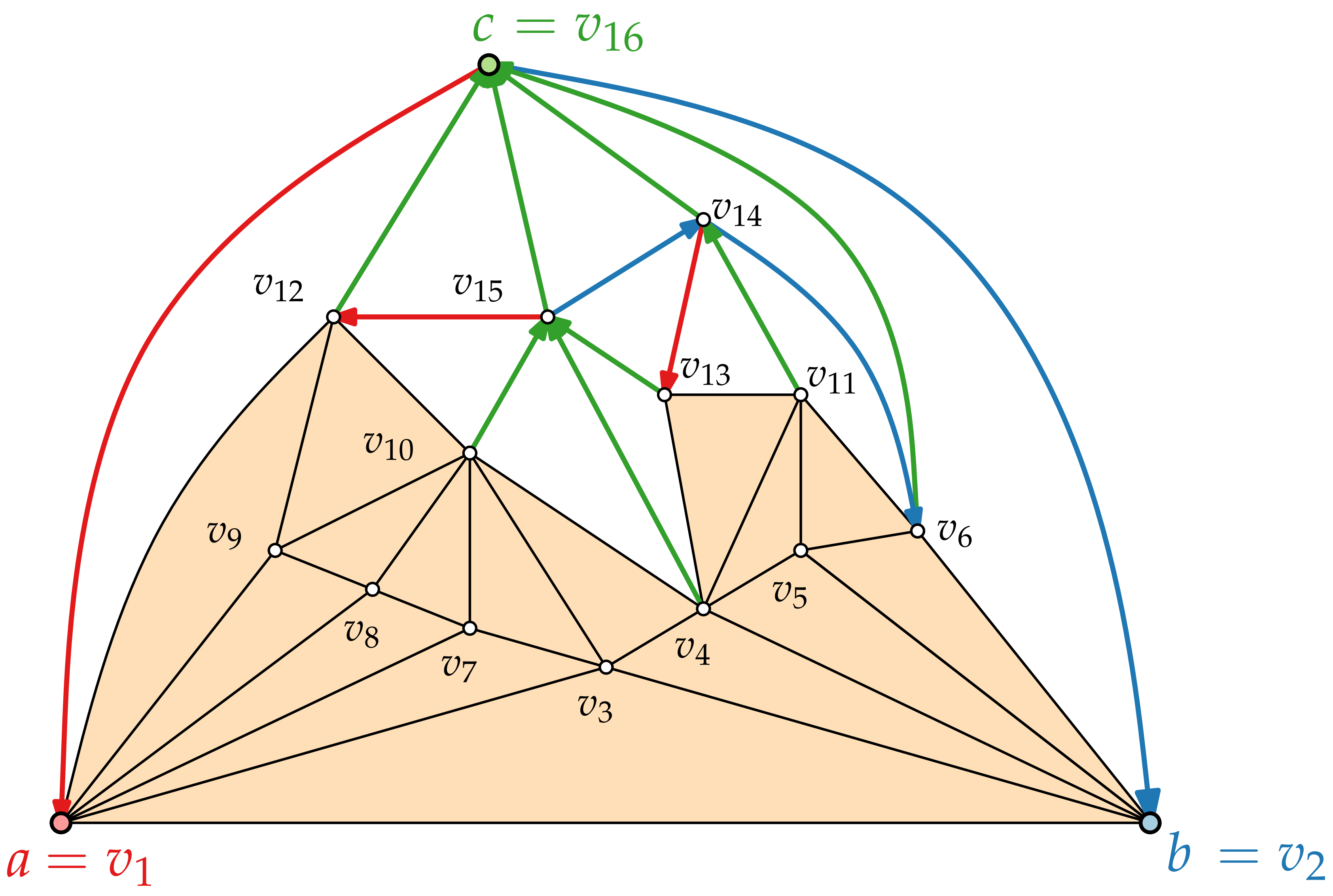
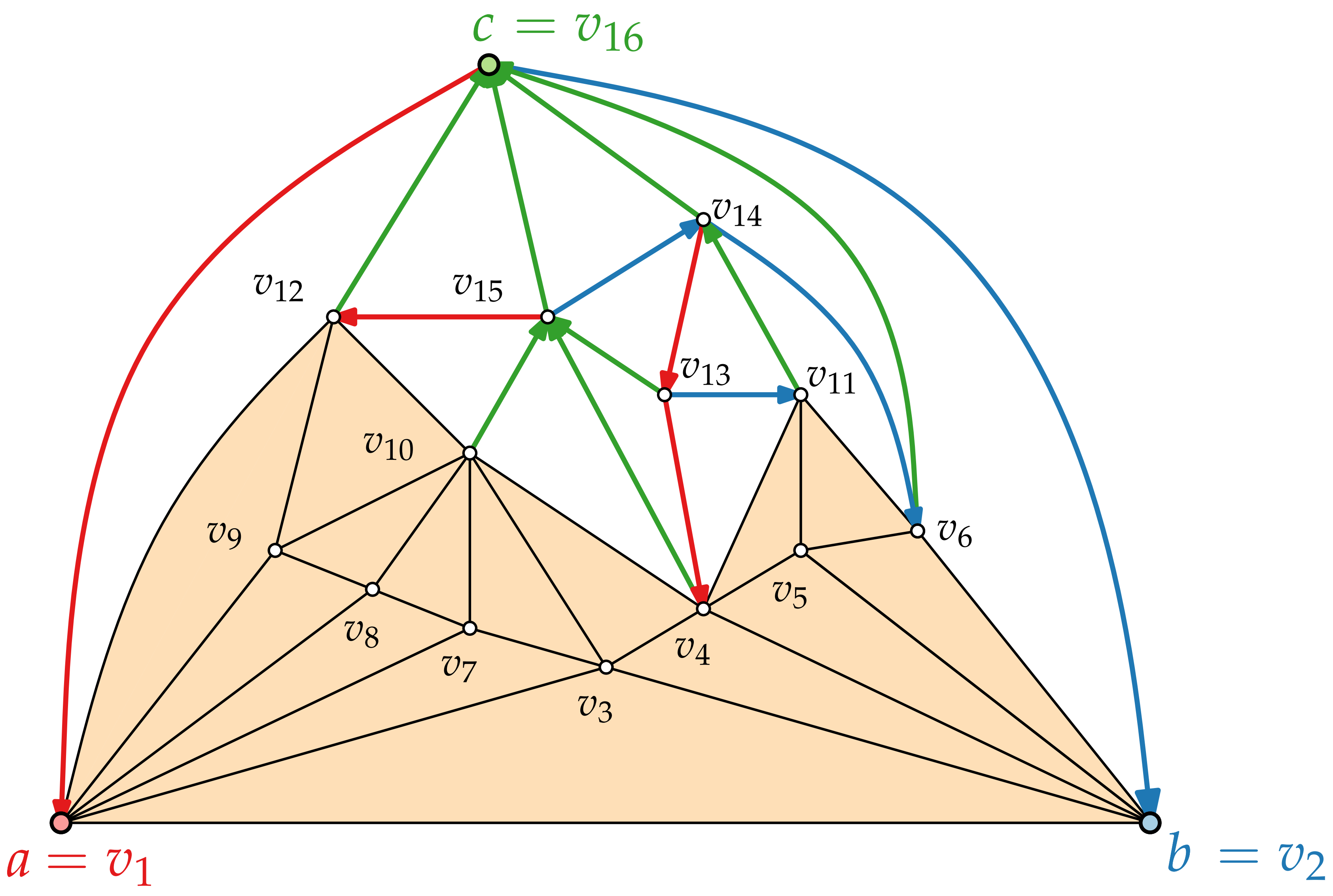
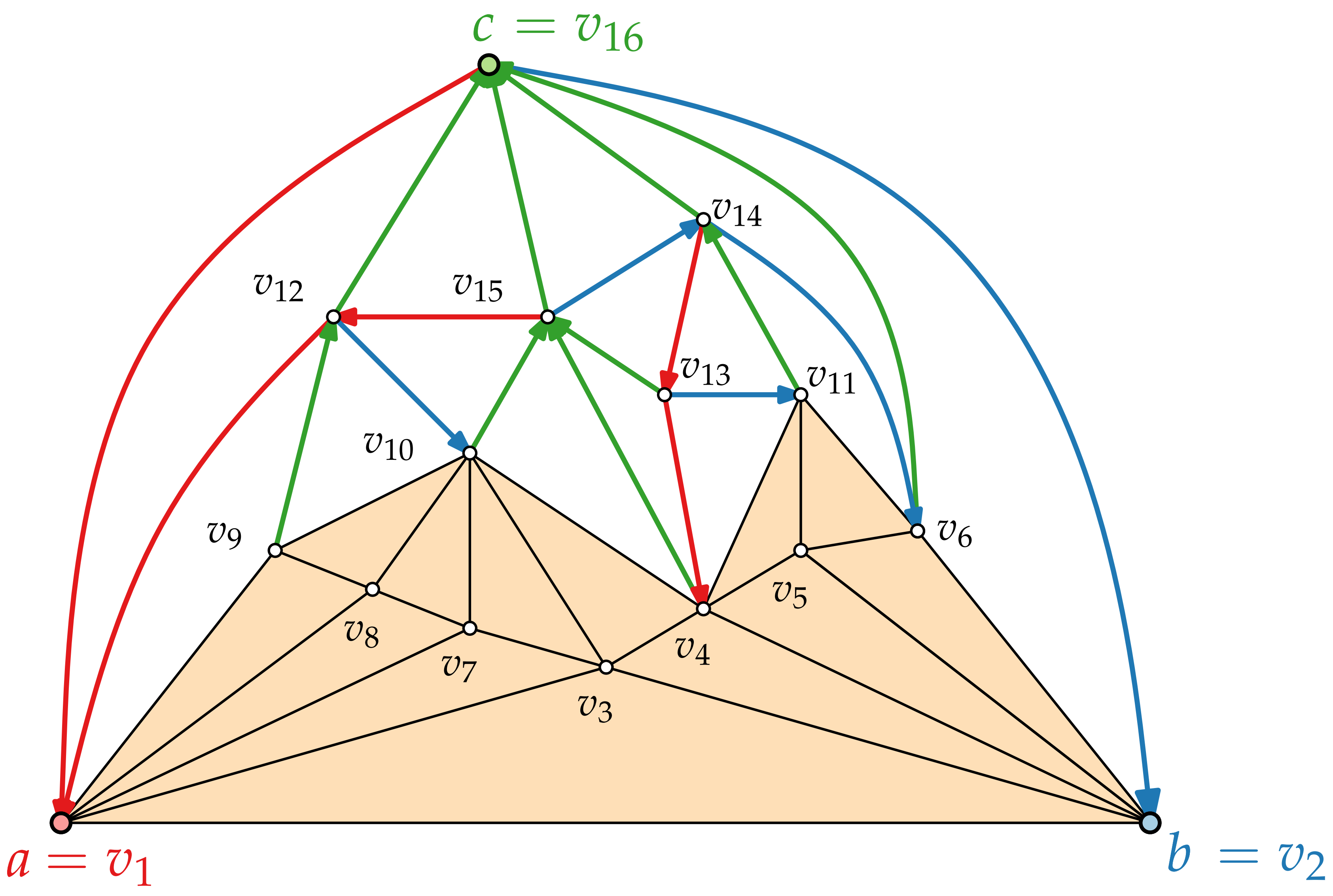


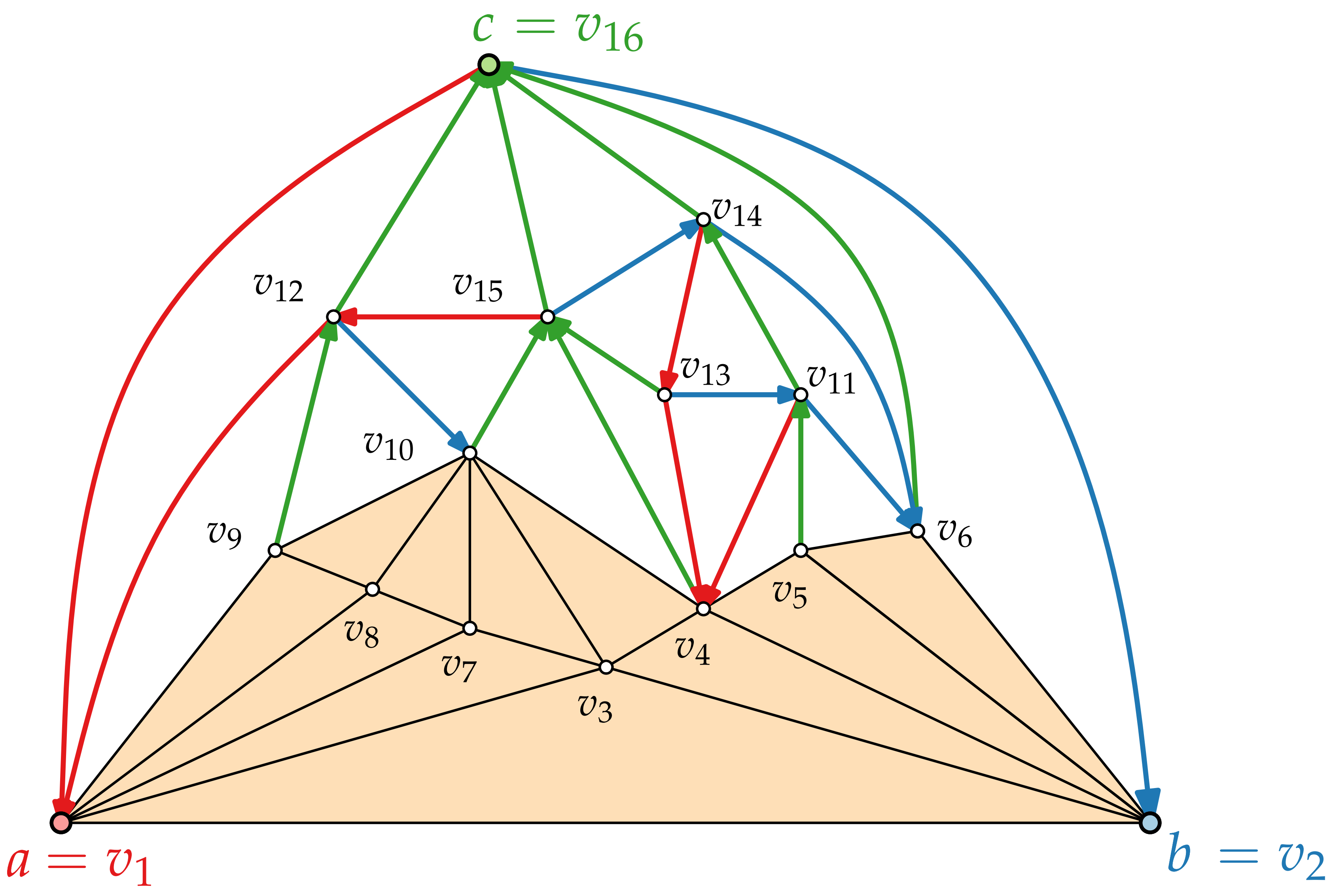
Canonical Order → Schnyder Realizer



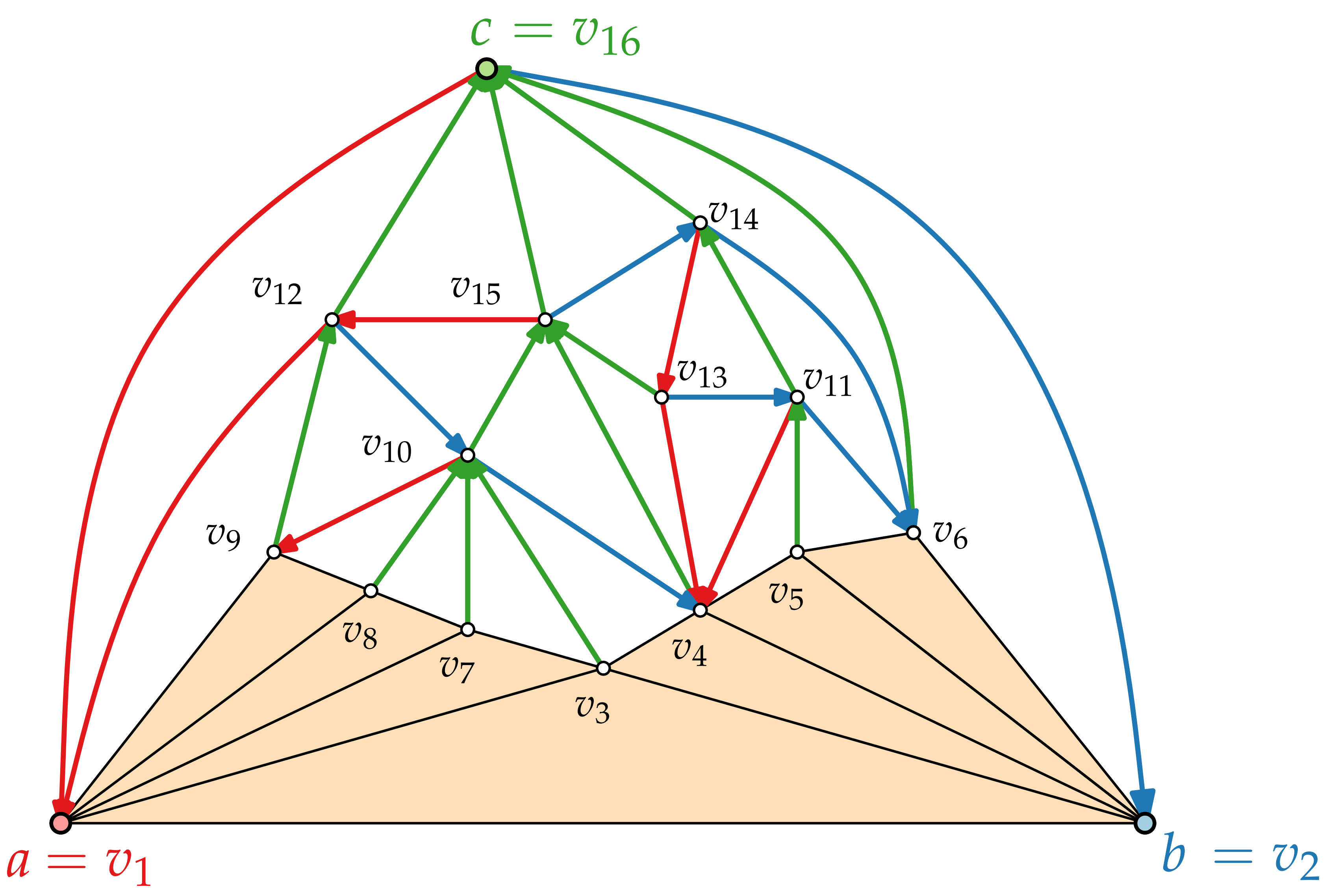
Canonical Order → Schnyder Realizer



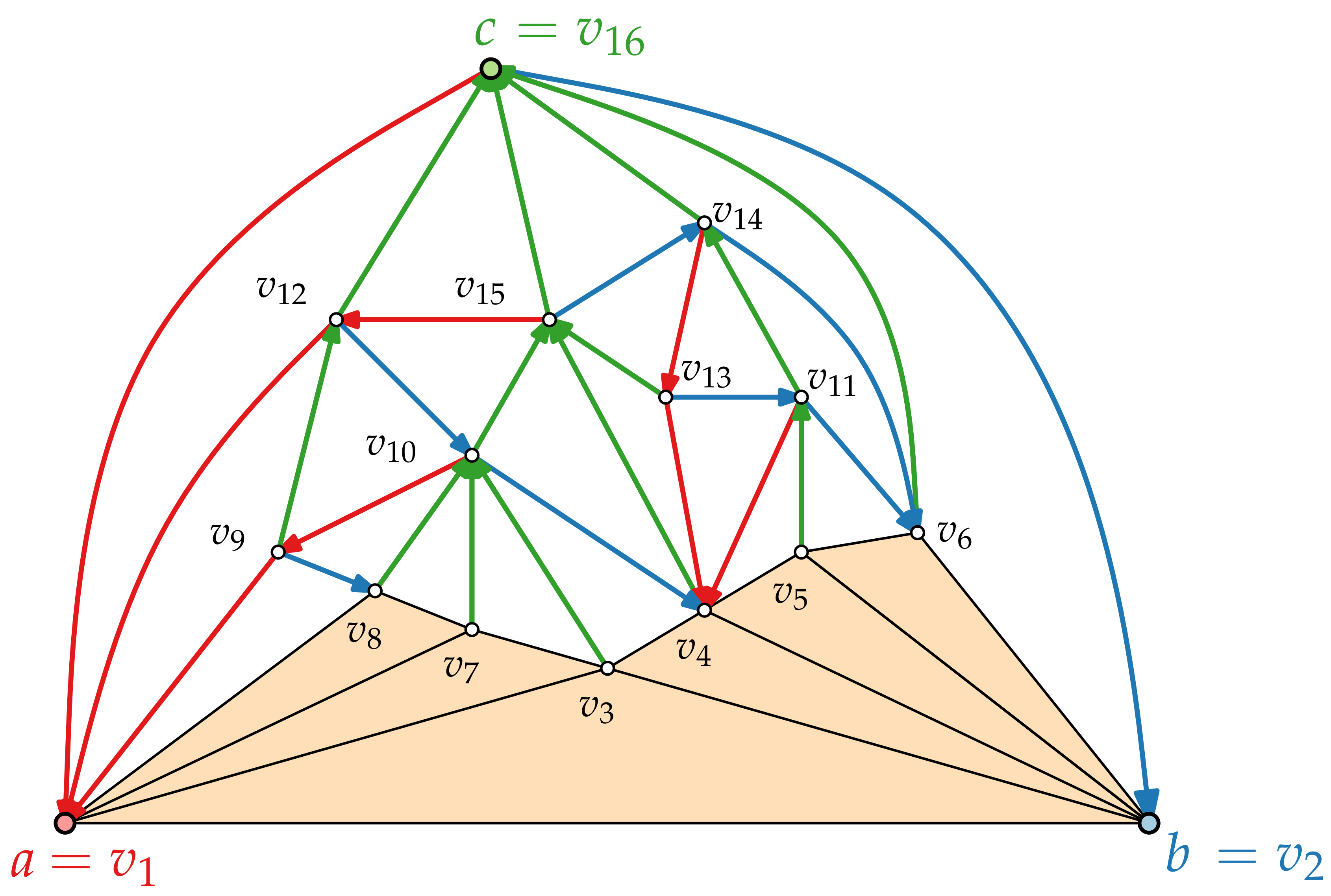
Canonical Order → Schnyder Realizer



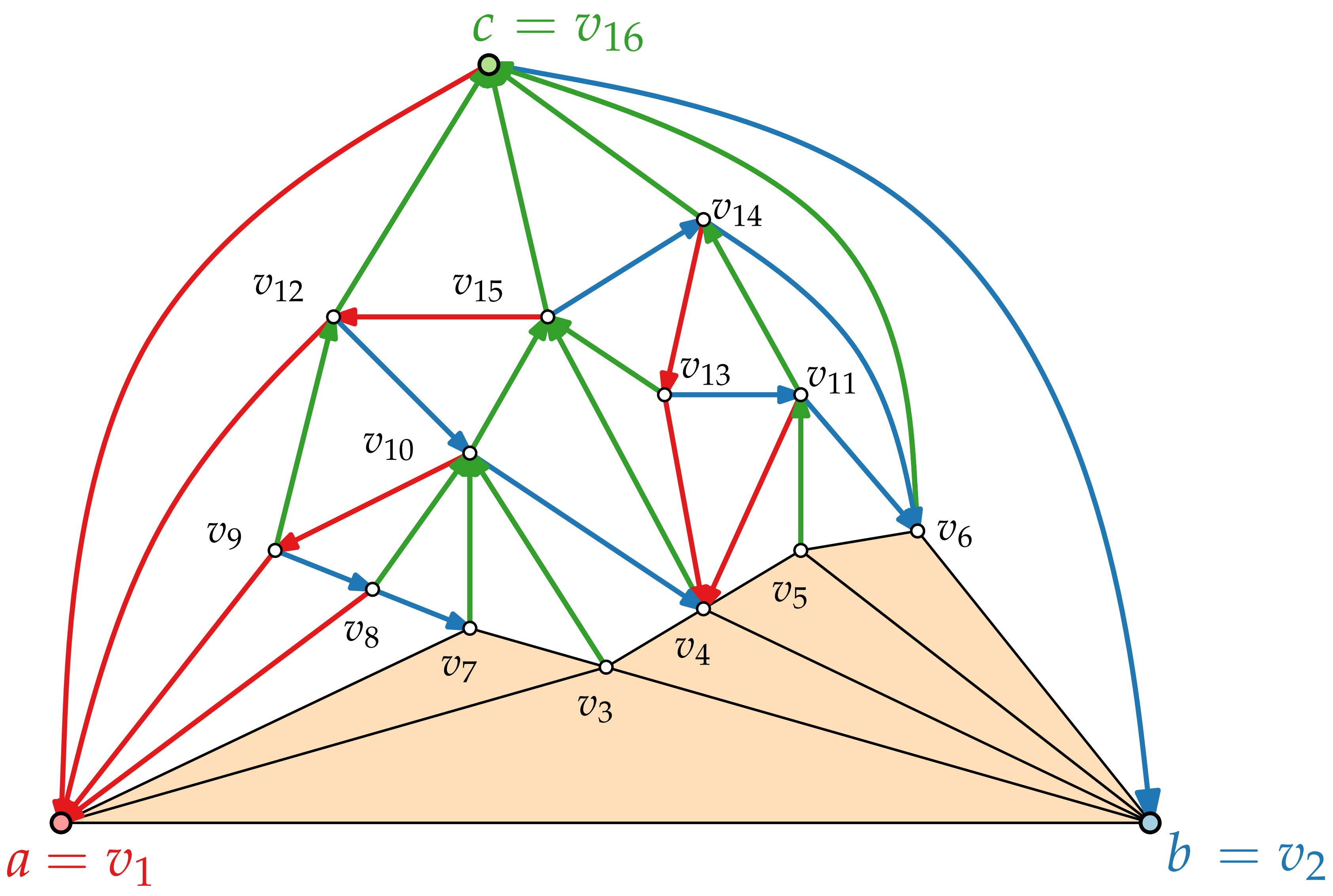
Canonical Order → Schnyder Realizer



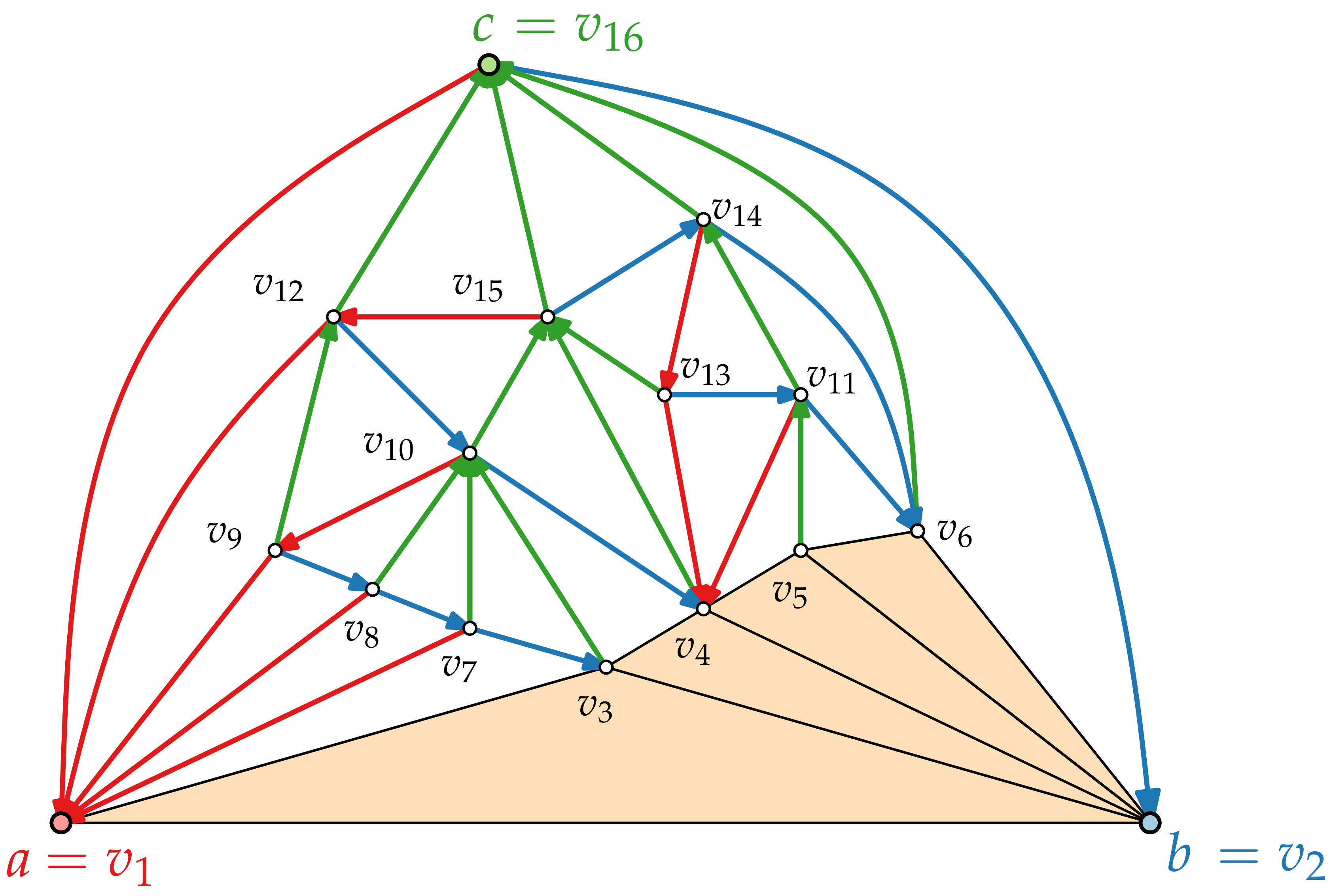
Canonical Order → Schnyder Realizer



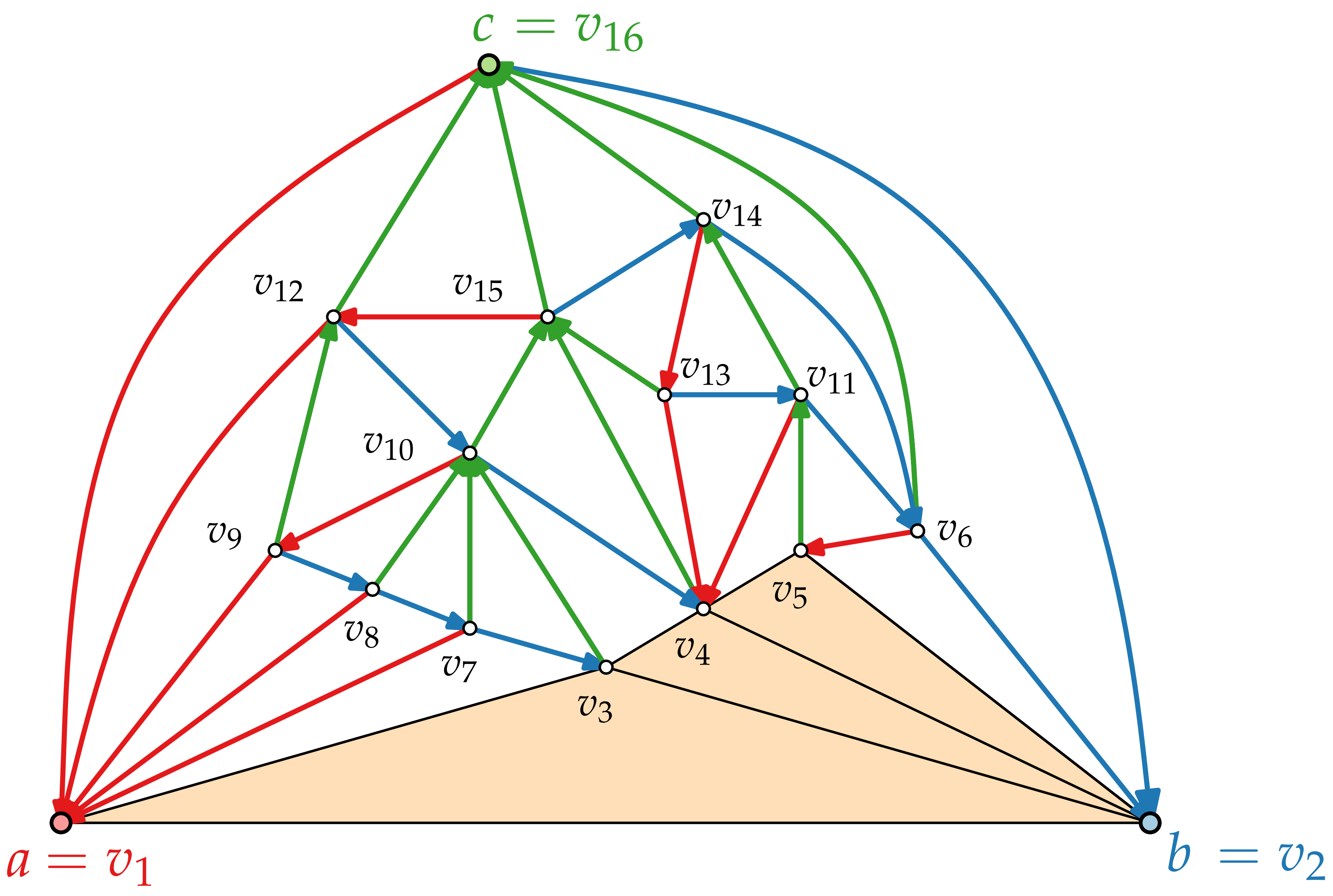
Canonical Order → Schnyder Realizer



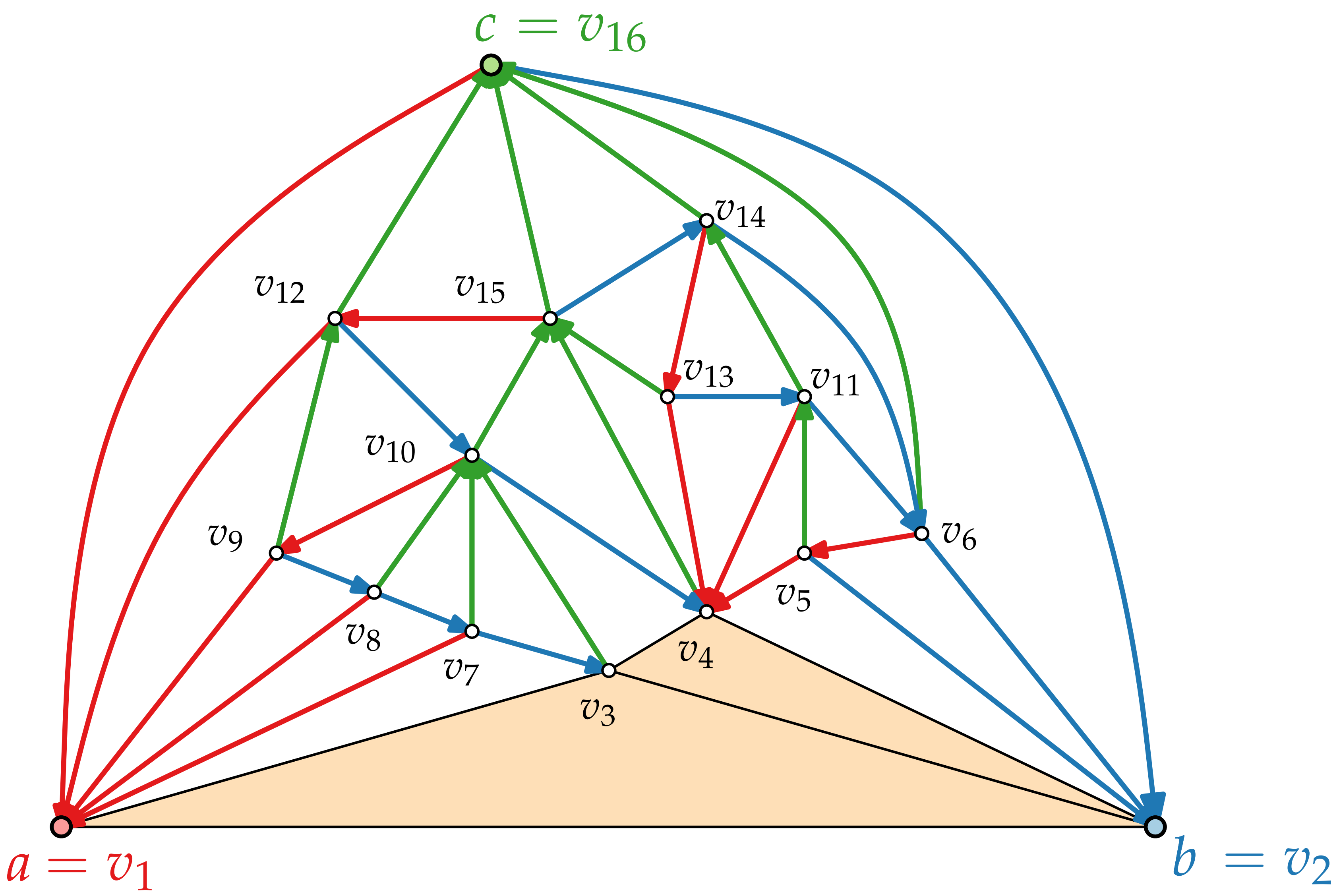
Canonical Order → Schnyder Realizer



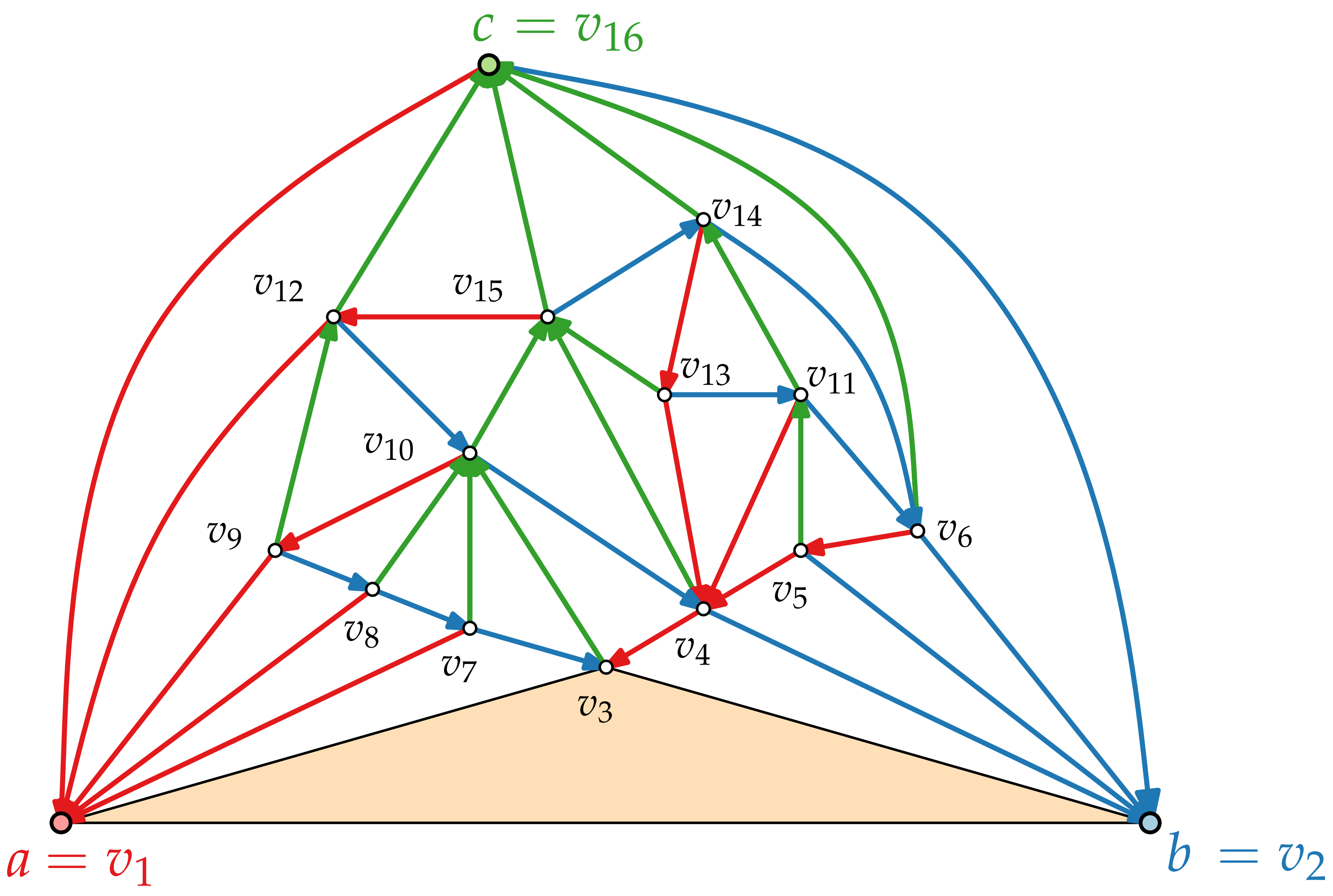
Canonical Order → Schnyder Realizer



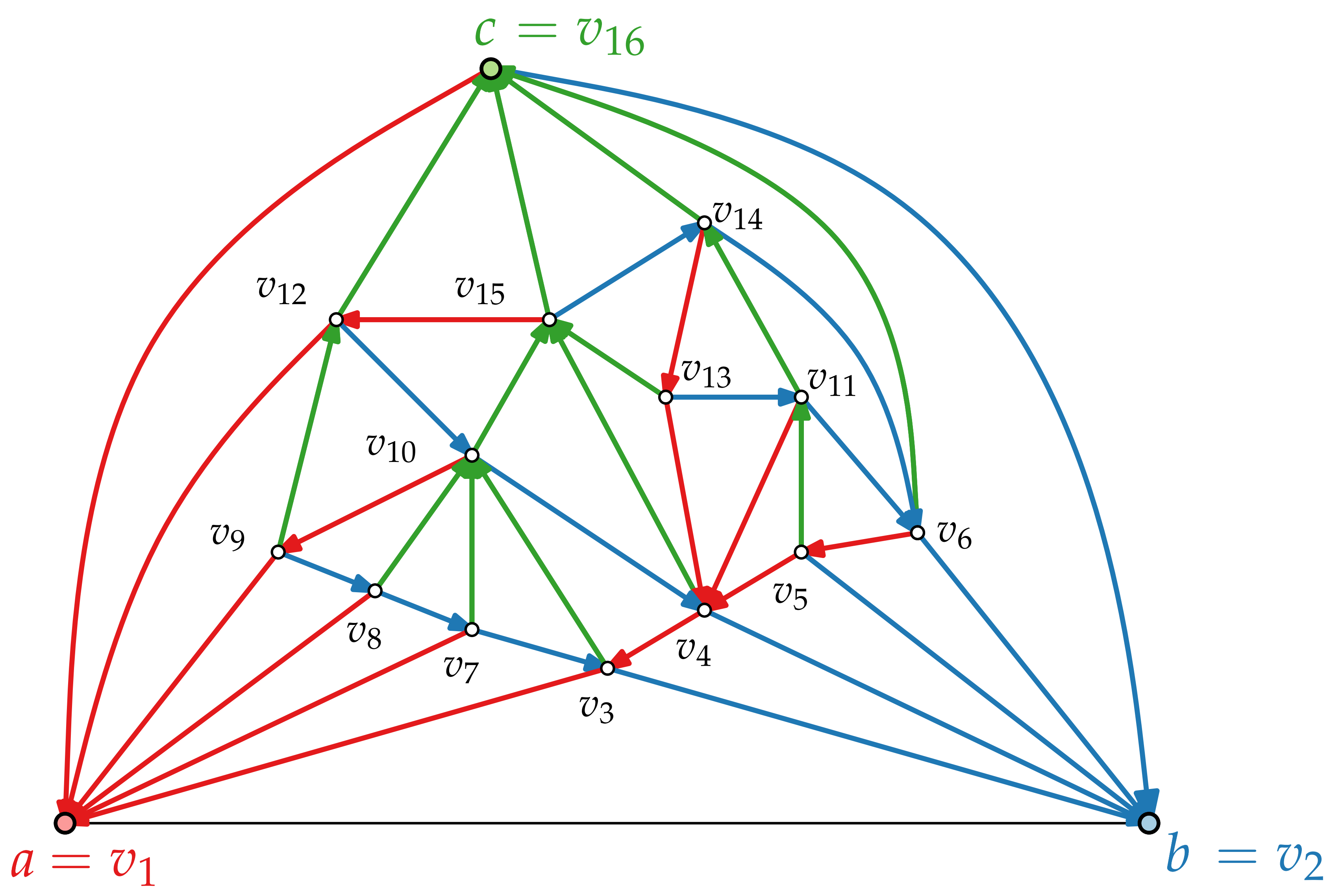
Canonical Order → Schnyder Realizer



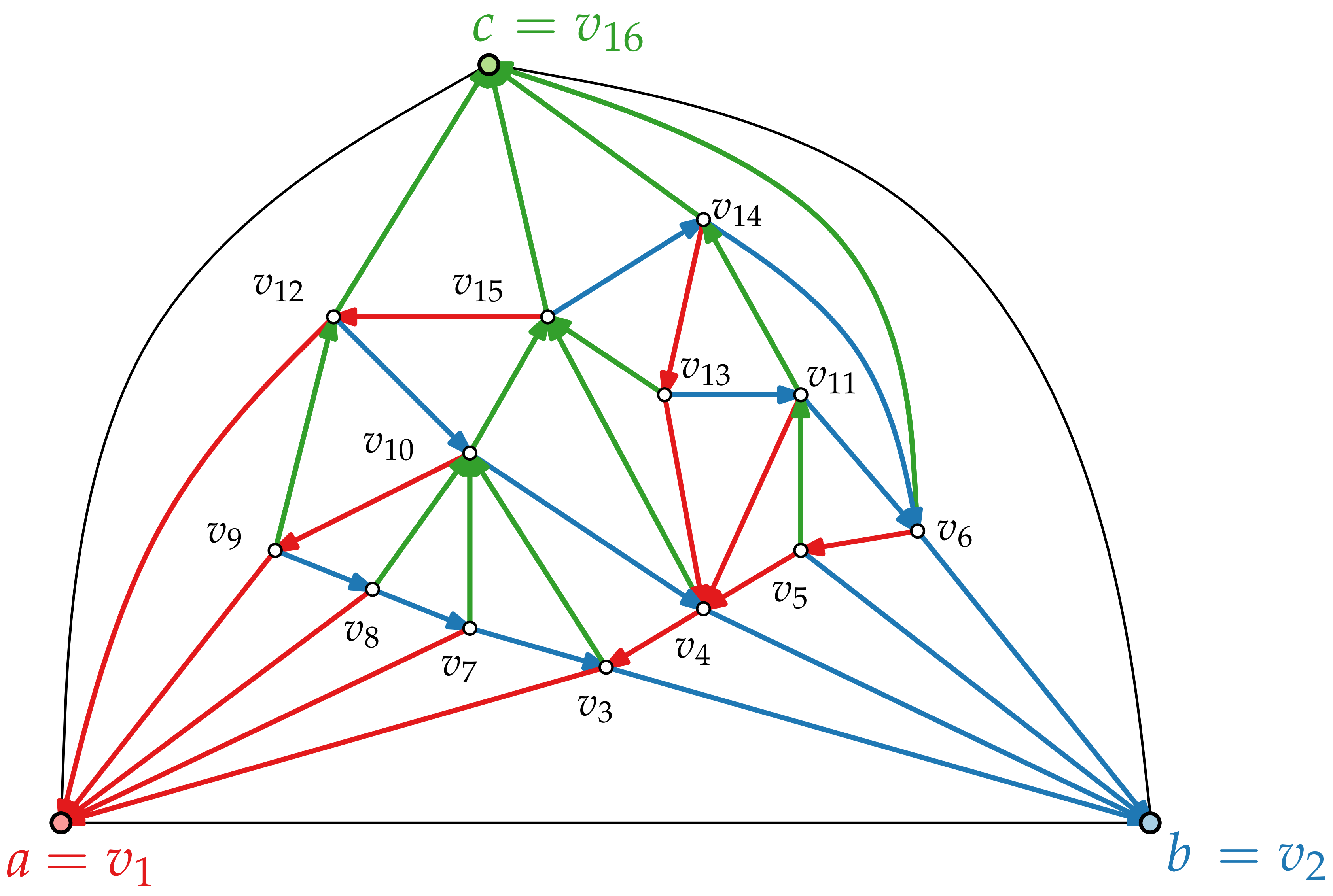
Canonical Order → Schnyder Realizer



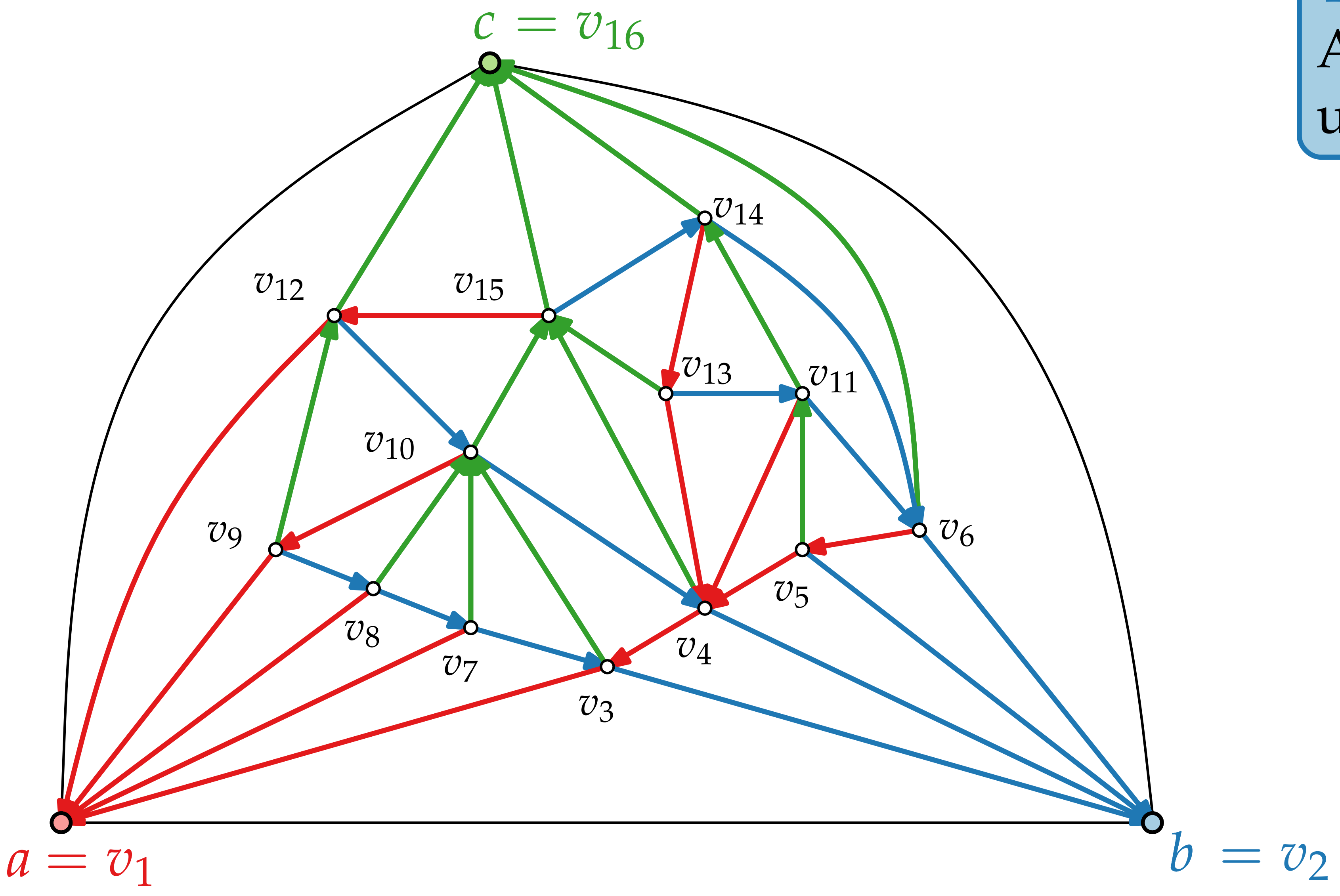
Canonical Order → Schnyder Realizer



Canonical Order → Schnyder Realizer

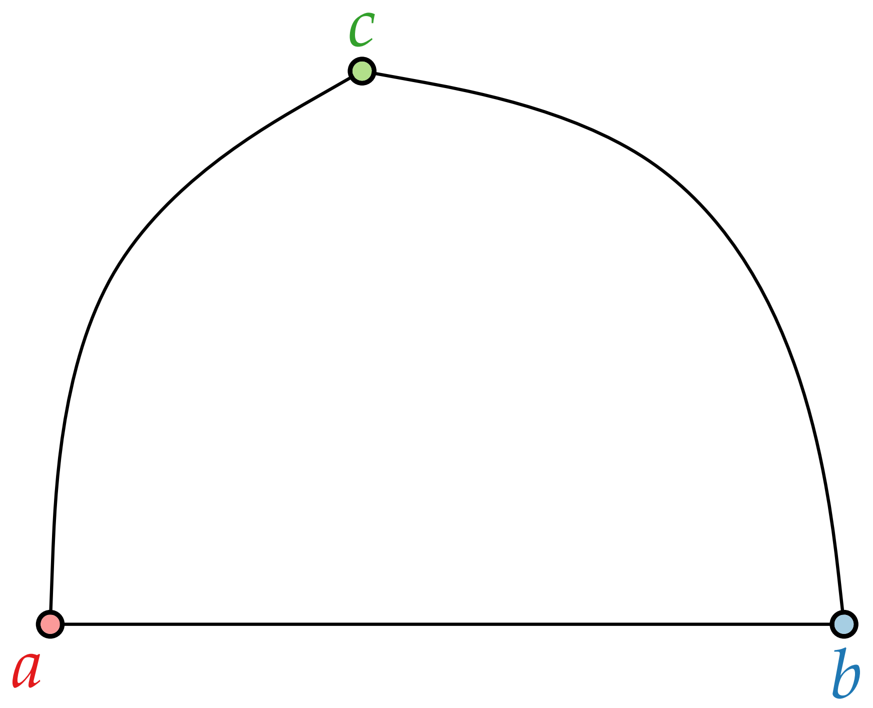


Canonical Order → Schnyder Realizer



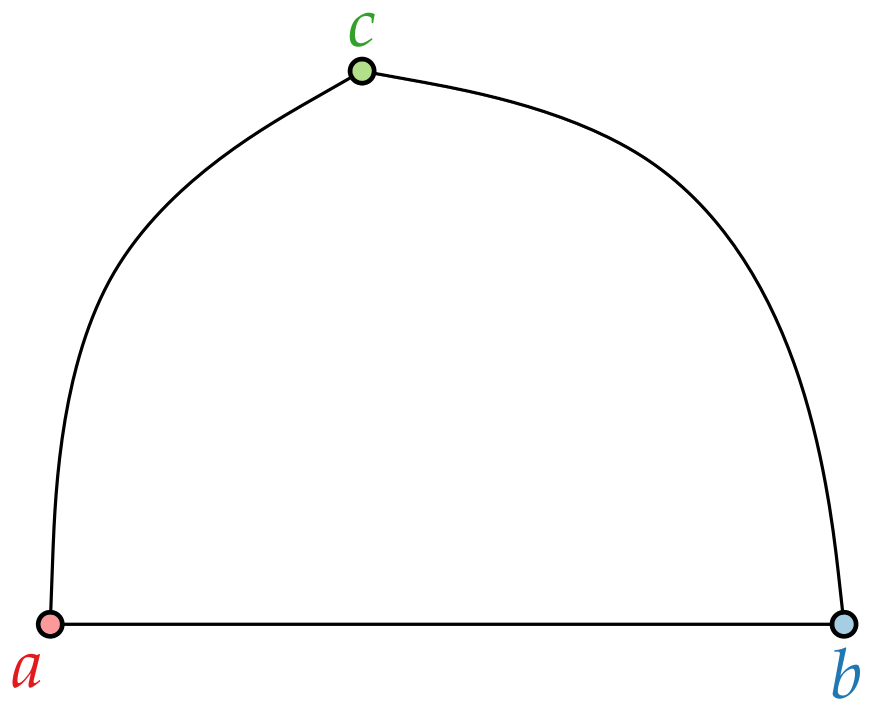
Theorem.
A canonical order induces a unique Schnyder Realizer.

Linear Time Computation



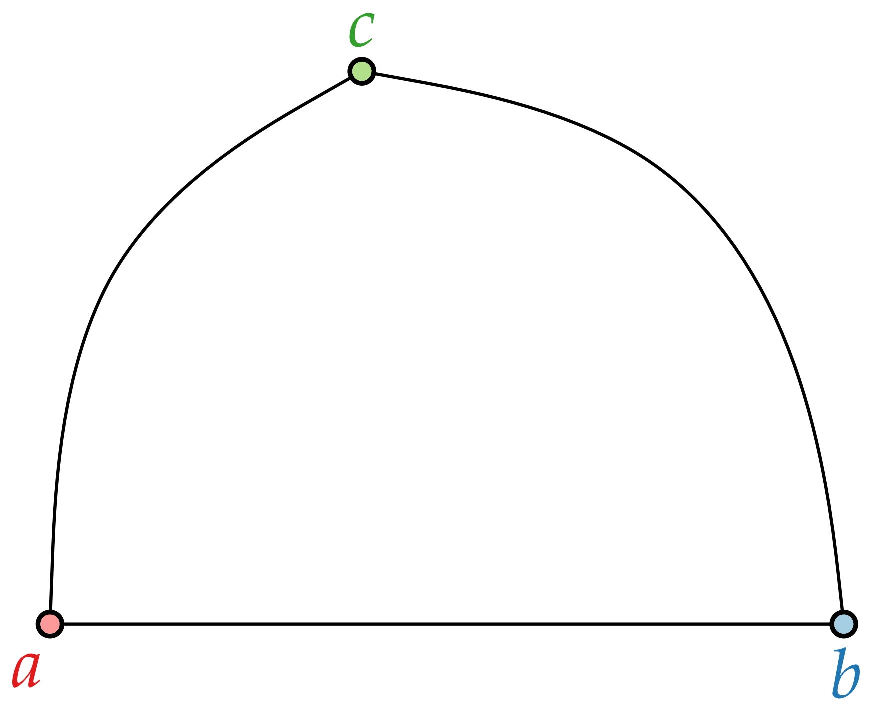
Linear Time Computation

- Compute Canonical Order



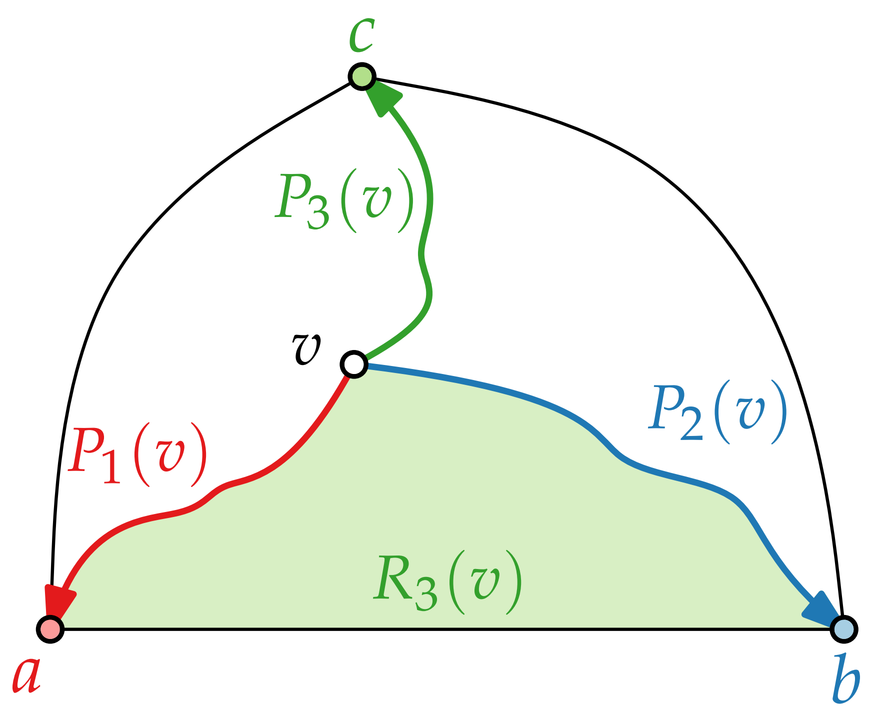
Linear Time Computation

- Compute Canonical Order
- Compute Schnyder Realizer



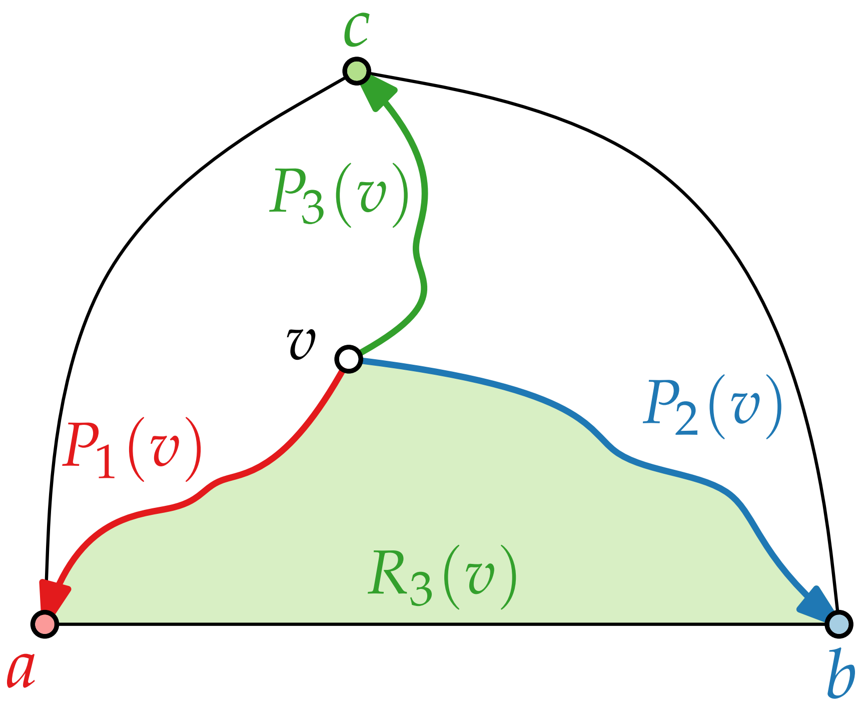
Linear Time Computation

- Compute Canonical Order
- Compute Schnyder Realizer



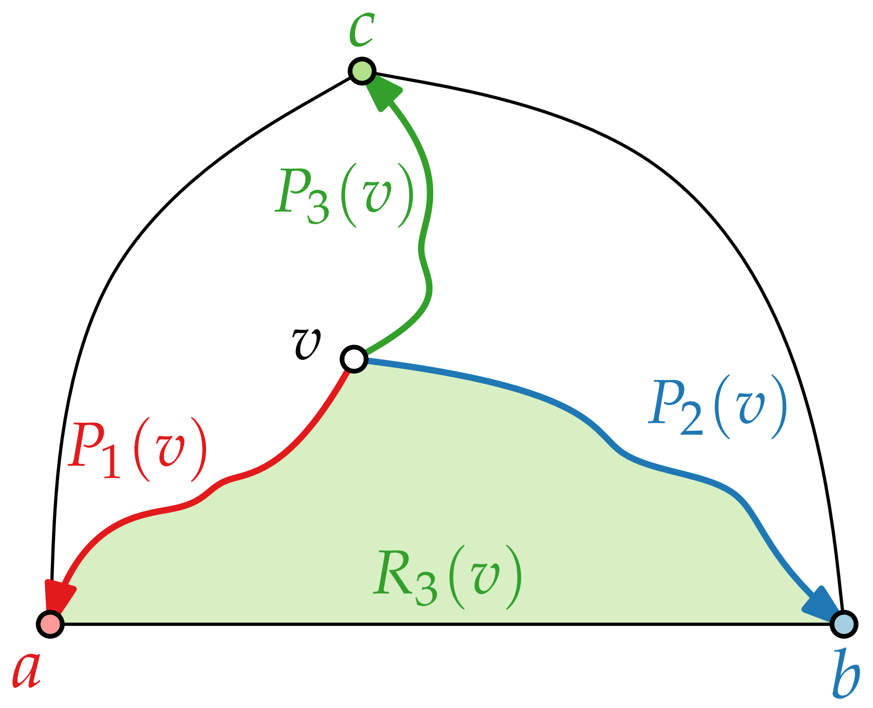
Linear Time Computation

- Compute Canonical Order
- Compute Schnyder Realizer
- Goal: $v_i = |V(R_i(v))| - |P_{i-1}(v)|$



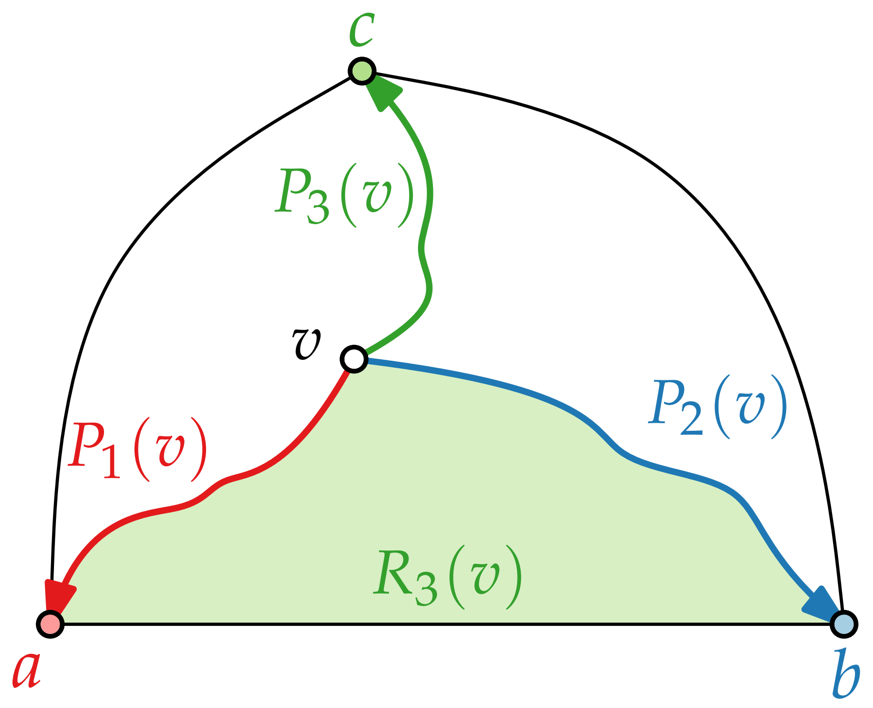
Linear Time Computation

- Compute Canonical Order
- Compute Schnyder Realizer
- Goal: $v_i = |V(R_i(v))| - |P_{i-1}(v)|$
- With traversal of each T_i, compute:



Linear Time Computation

- Compute Canonical Order
- Compute Schnyder Realizer
- Goal: $v_i = |V(R_i(v))| - |P_{i-1}(v)|$
- With traversal of each T_i, compute:
  - The number of vertices in $P_i(v)$



Linear Time Computation

- Compute Canonical Order
- Compute Schnyder Realizer
- Goal: $v_i = |V(R_i(v))| - |P_{i-1}(v)|$
- With traversal of each T_i, compute:
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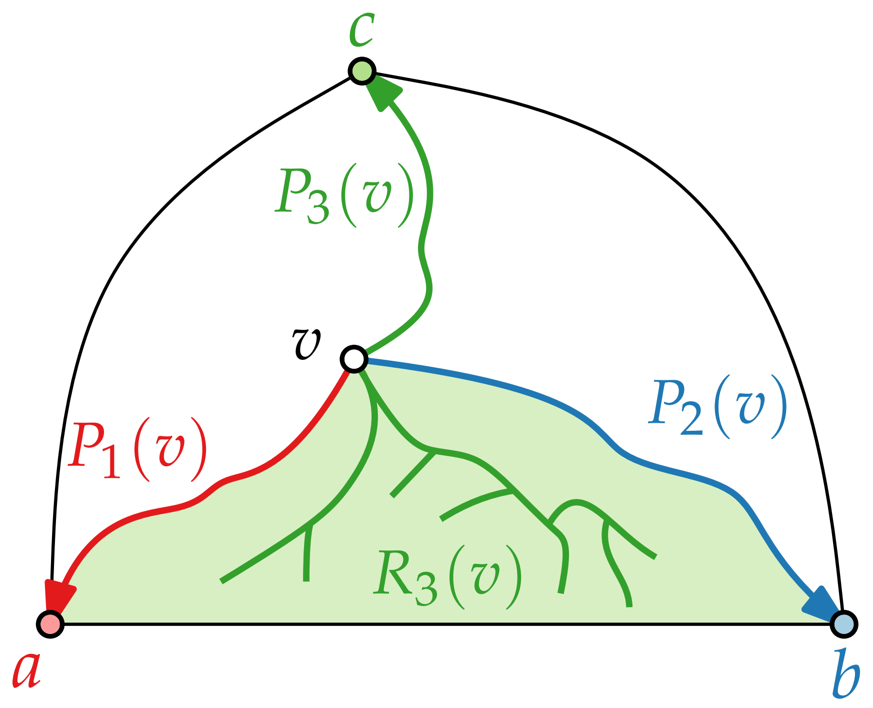
  - The number of vertices in the subtree $T_i(v)$ of T_i rooted at v



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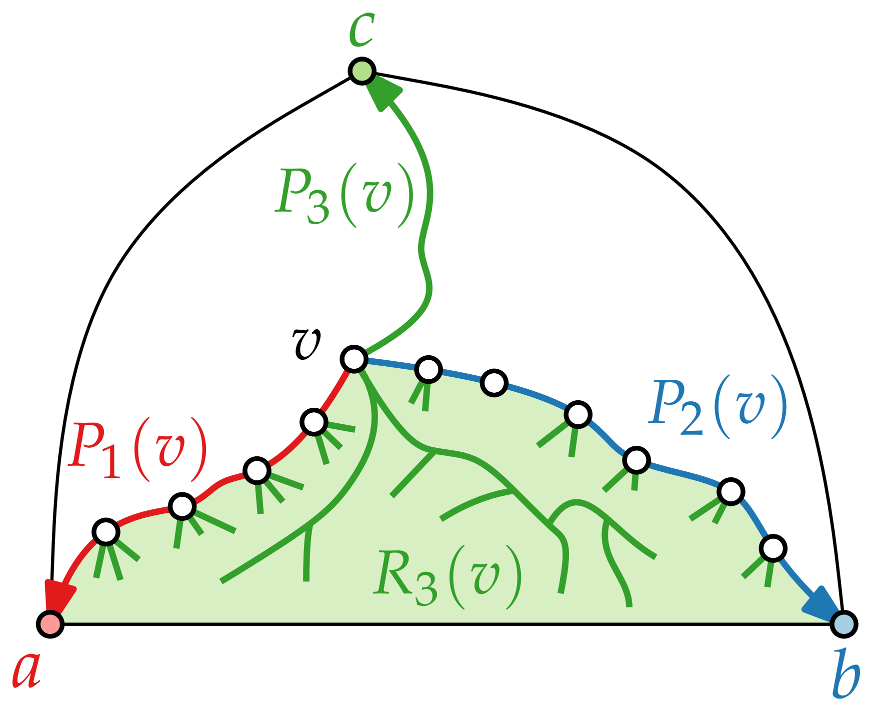

Linear Time Computation

- Compute Canonical Order
- Compute Schnyder Realizer
- Goal: $v_i = |V(R_i(v))| - |P_{i-1}(v)|$
- With traversal of each T_i, compute:
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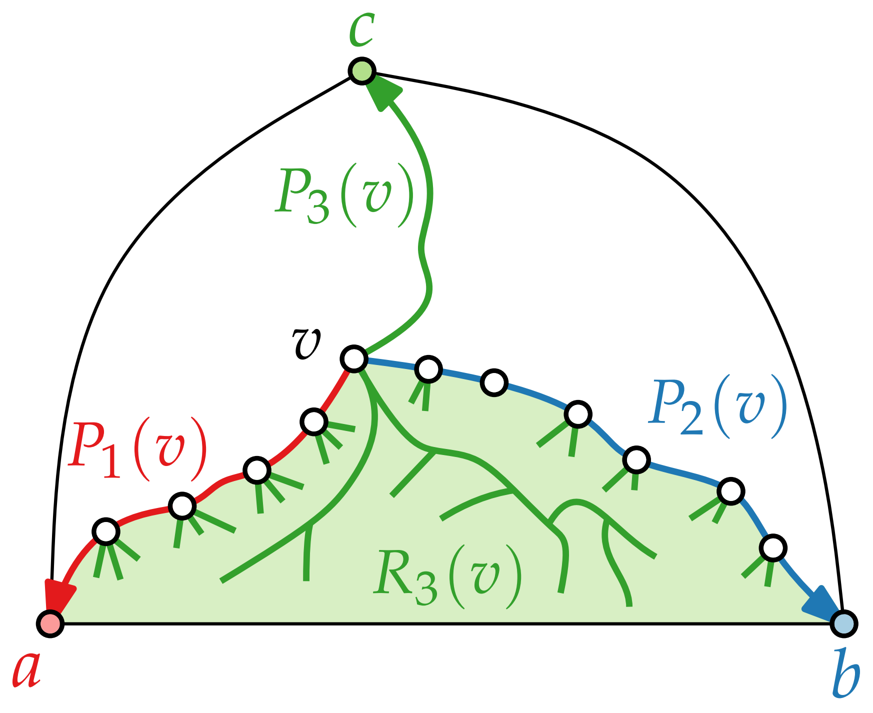
  - The number of vertices in the subtree $T_i(v)$ of T_i rooted at v
- $|V(R_i(v))| =$



Linear Time Computation

- Compute Canonical Order
- Compute Schnyder Realizer
- Goal: $v_i = |V(R_i(v))| - |P_{i-1}(v)|$
- With traversal of each T_i, compute:
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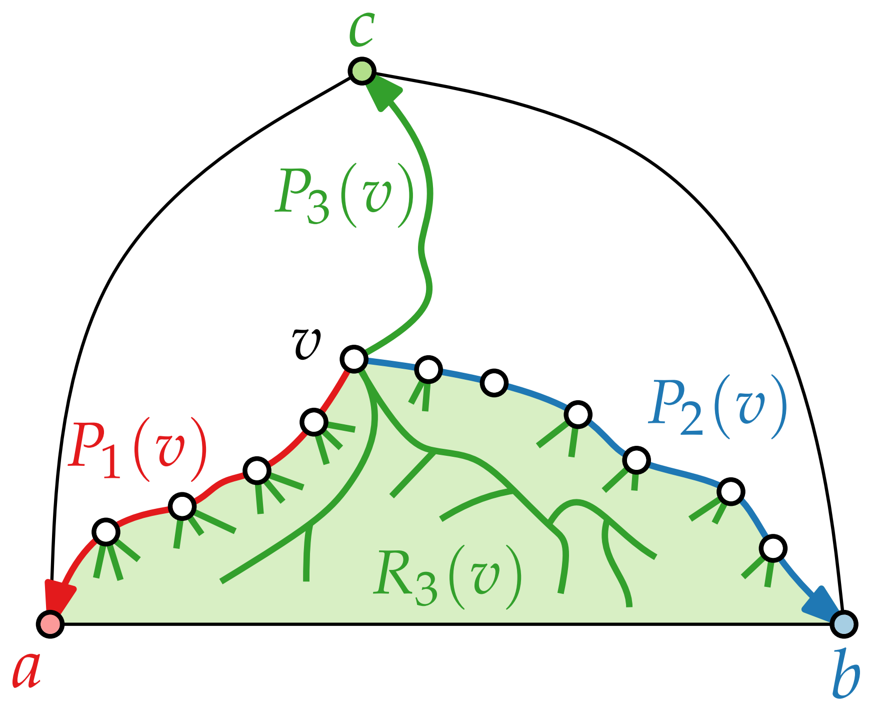
  - The number of vertices in the subtree $T_i(v)$ of T_i rooted at v
- $|V(R_i(v))| = \sum_{u \in P_{i+1}(v)} |T_i(u)|$



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- Compute Canonical Order
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- With traversal of each T_i, compute:
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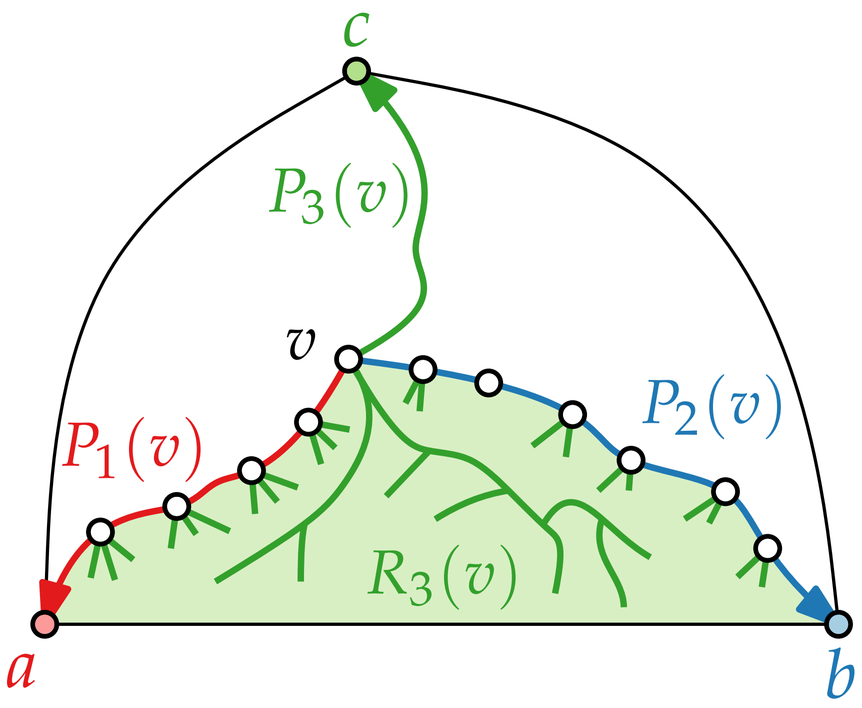
- $|V(R_i(v))| = \sum_{u \in P_{i+1}(v)} |T_i(u)| + \sum_{u \in P_{i-1}(v)} |T_i(u)|$



Linear Time Computation

- Compute Canonical Order
- Compute Schnyder Realizer
- Goal: $v_i = |V(R_i(v))| - |P_{i-1}(v)|$
- With traversal of each T_i, compute:
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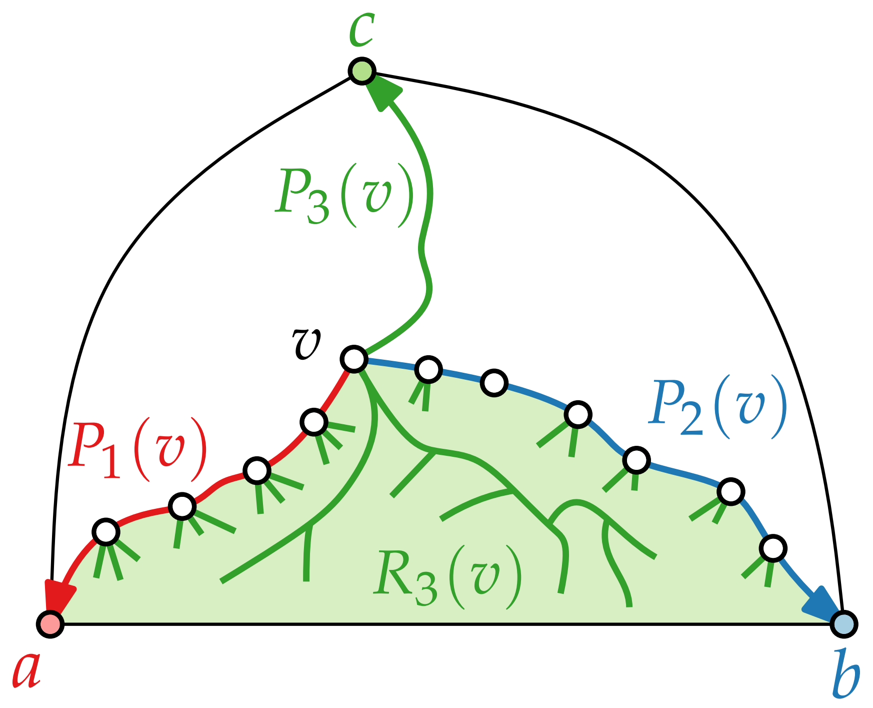
- $|V(R_i(v))| = \sum_{u \in P_{i+1}(v)} |T_i(u)| + \sum_{u \in P_{i-1}(v)} |T_i(u)| - T_i(v)$



Linear Time Computation

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- Goal: $v_i = |V(R_i(v))| - |P_{i-1}(v)|$
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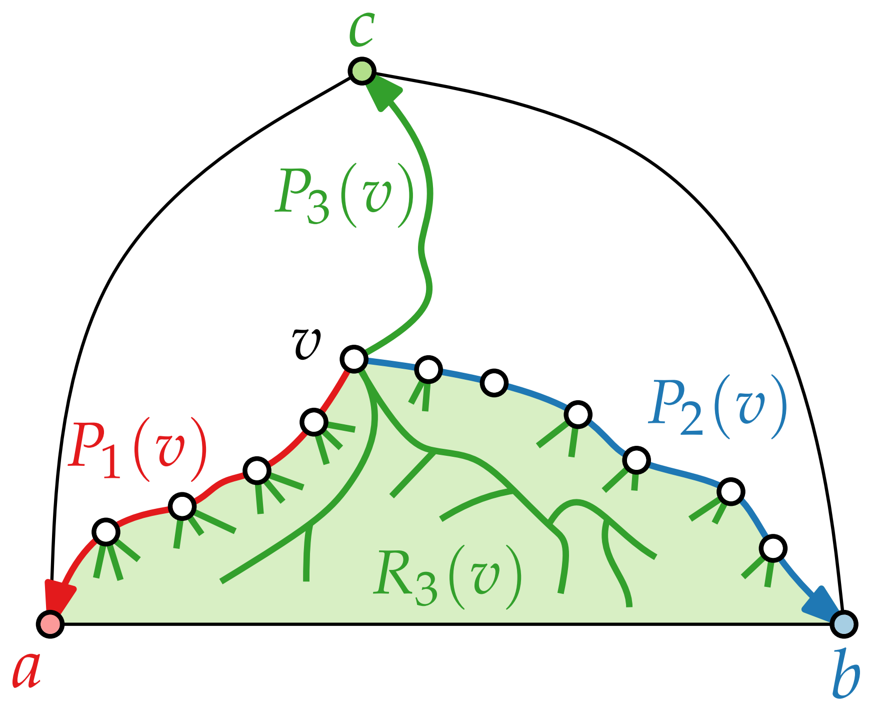
- $|V(R_i(v))| = \sum_{u \in P_{i+1}(v)} |T_i(u)| + \sum_{u \in P_{i-1}(v)} |T_i(u)| - T_i(v)$
- Compute these sums in six tree traversals



Linear Time Computation

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- Goal: $v_i = |V(R_i(v))| - |P_{i-1}(v)|$
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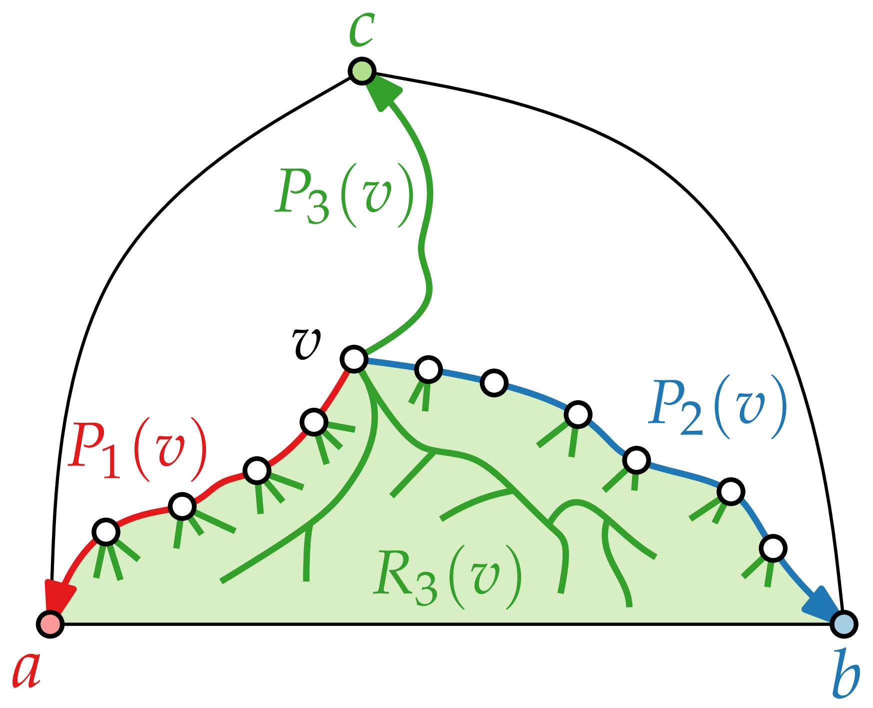
- $|V(R_i(v))| = \sum_{u \in P_{i+1}(v)} |T_i(u)| + \sum_{u \in P_{i-1}(v)} |T_i(u)| - T_i(v)$
- Compute these sums in six tree traversals



Theorem. [Schnyder '90]
Every n-vertex planar graph has a planar straight-line drawing of size $(n-2) \times (n-2)$. Such a drawing can be computed in $O(n)$ time.