This Is Time in Graph Drawing

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BGPlay

- My starting point (time): Bgplay
  - gdb Mariani Patrignani Pizzonia, Bgplay: A System for Visualizing the Interdomain Routing Evolution, GD 2003
  - part of the RIPE Stat service
    - its Web page is visited an average of more than five thousands times per day
  - also available at RouteViews, BGPStream, and Isolario

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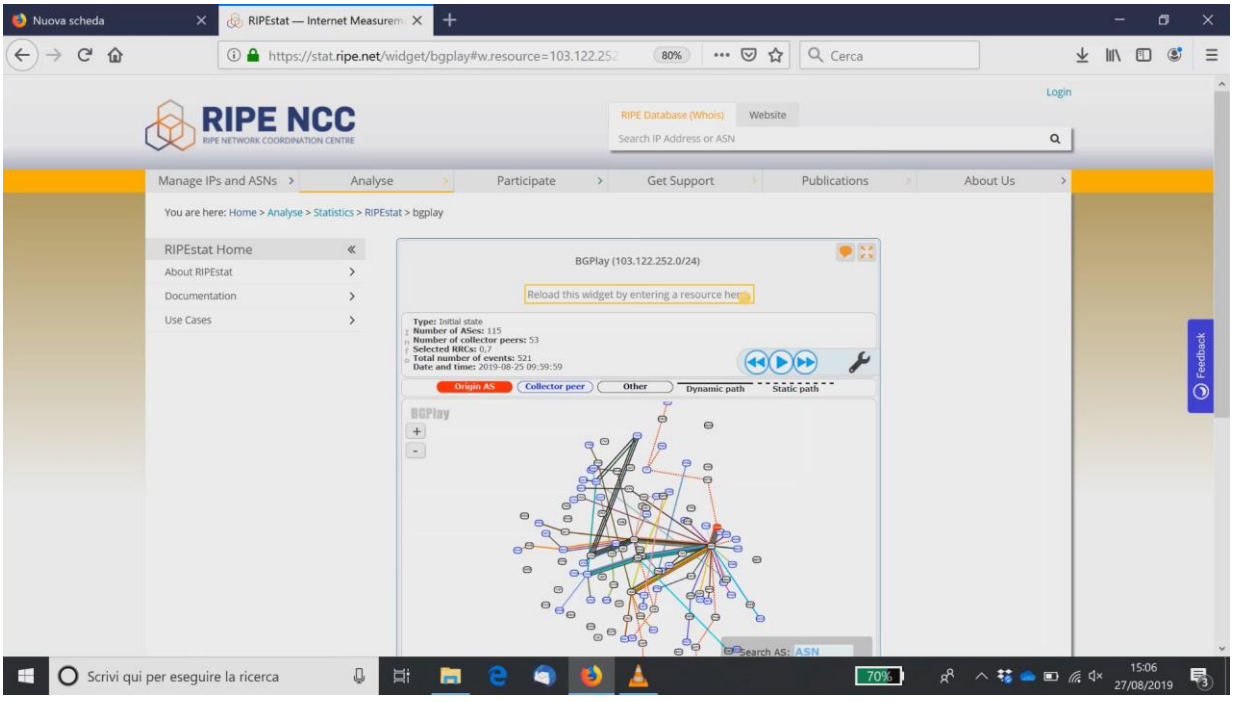

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The concept of time in Graph Drawing

- One of the main challenges for Graph Drawing is the relationship between drawings and time
  - Show the temporal evolution of the visualized graphs
- About 40 papers on the subject in the GD Conferences
- Main GD fields related to *time*
  - dynamic algorithms, streaming, animation, time reconciliation, storyline, morphs, human perception

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The point of view of the InfoVis community

- Visualization metaphor
  - Node-link or matrices
- Span of knowledge on data
  - Offline if, at any time instant, future data are known and can be used to compose the drawing
  - Online otherwise
- Representation of time
  - Animation or timeline
- Mental map preservation
- Modeling of transitions

Beck, Burch, Diehl, Weiskopf, The state of the art in visualizing dynamic graphs, Eurovis 2014

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Purpose and limits of this talk

- Assess the maturity level of GD on the topic
- Mainly focusing on
  - Personal experience
  - Combinatorial algorithms
  - Straight-line drawings
  - Networking applications
- General methods
- Open problems

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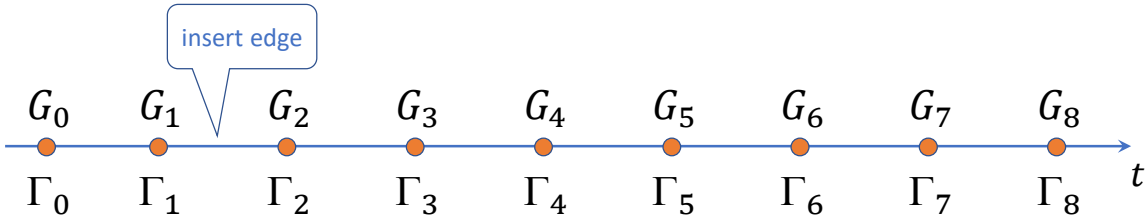
Graph stories and drawing stories

- A *graph story* is a sequence $G_0 \cdots G_n$ of graphs, where G_{i+1} is obtained from G_i by applying an *update operation*
- A *drawing story* $\Gamma_0 \cdots \Gamma_n$ of a graph story $G_0 \cdots G_n$ is a sequence of drawings such that Γ_i is a drawing of G_i



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Type of graph stories and of drawing stories

- A graph story is a *tree story* or a *forest story* or a *planar graph story* or …. if all G_i's are trees or forests or planar graphs or ….
- A drawing story is *planar* or *straight-line* or …. if all its drawings are planar or straight-line or ….

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Dynamic Algorithms

	Animation	Timeline
Offline		
Online	Dynamic Algorithms	

The drawing story is *not* known in advance

Rely on an *implicit* representation of the drawing

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A Dynamic GD Problem

- Type of the graph story and type of the drawing story
- Repertory of update operations
  - E.g. insertion of vertices and edges
- Queries on the current drawing
  - E.g. draw subgraph, draw window
- Dynamic drawing predicate
  - Similarity properties of consecutive drawings

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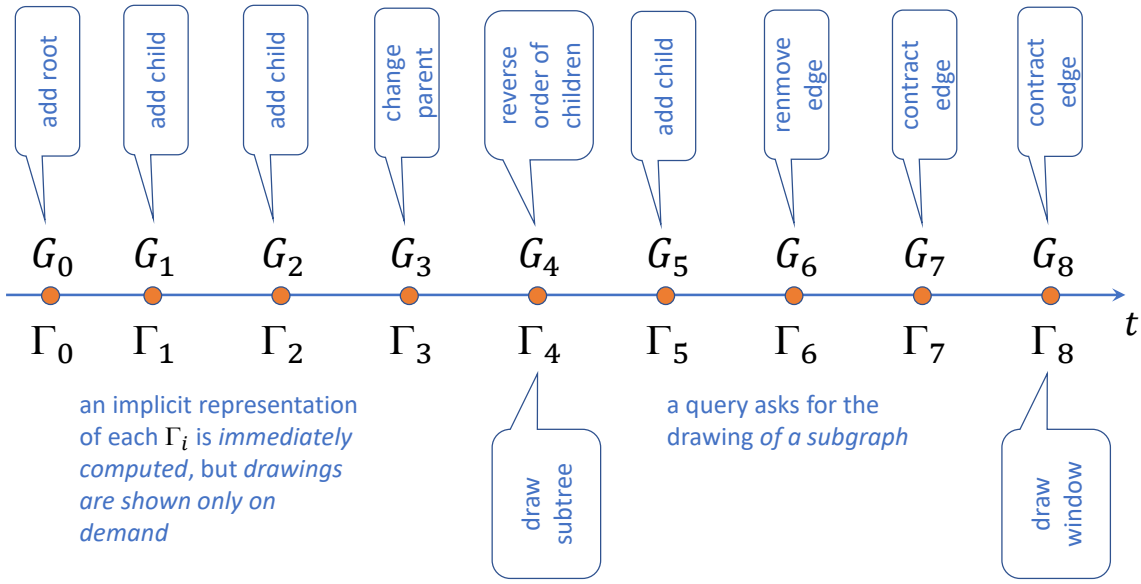
Dynamic GD – a drawing story of a forest story



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Selected contributions

- Cohen gdb Tamassia Tollis Bertolazzi, A framework for dynamic graph drawing, SoCG 1992
- Cohen gdb Tamassia Tollis, Dynamic graph drawings: Trees, series-parallel digraphs, and planar st-digraphs, SICOMP 1995
- Papakostas Tollis, Incremental orthogonal graph drawing in three dimensions, GD 1997
- Bachl, Semi-dynamic orthogonal drawings of planar graphs, GD 2002

- Plus several papers that focus on the topology of the drawing, e.g. dynamic planarity testing

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Some results

Graph story	Drawing story	Memory	Update time	Draw subgraph time	Draw window time	Overall area
Forest of rooted trees	Upward planar straight-line grid	$O(n)$	$O(\log n)$	$O(k + \log n)$ Subtree	$O(k \log n)$	$O(n^2)$
Series-parallel digraphs	Upward planar straight-line grid	$O(n)$	$O(\log n)$	$O(k + \log n)$ Series-parallel subgraph	$O(k \log^2 n)$	$O(n^2)$
Planar st-digraphs	Upward planar *polyline* grid	$O(n)$	$O(\log n)$	$O(k \log n)$	-	$O(n^2)$

n is the total number of vertices and k is the number of vertices to be drawn

targets: a time that is: (1) sublinear in n for updates and (2) linear in the number of objects to be drawn and sublinear in n for drawing queries

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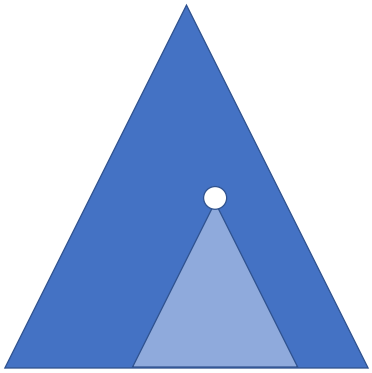
Dynamic GD – methods

- Maintain a tree decomposition of the graph equipped with variables representing the features of the drawing
- The decomposition is implemented using dynamic trees



The position of a node in the drawing depends on several features of the subtrees rooted at that node

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Dynamic GD – problems

- Currently, the tree drawings that are maintained use the x-coordinates of an in-order traversal; is it possible to maintain Rengold-Tilford-type drawings?
- Maintain a straight-line grid drawing of a planar graph (e.g. a Schnyder-wood)

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Streaming

	Animation	Timeline
Offline		
Online	Streaming	

The drawing story is *not* known in advance

When an *object* (vertex/edge) arrives, it is explicitely drawn, its placement cannot (almost) be altered, objects have a given *persistence*

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A Streaming GD Problem

- A source produces a sequence of n objects (vertices/edges) that are immediately and explicitely drawn
- The *persistence* of an object specifies how much time it remains in the drawing; tipically all objects have the same persistence (also called *window* size) $k \ll n$
- Once an object is drawn, its placement *cannot be altered* until it is removed (k instants after it was produced)
- All drawings should fit an area that is a function of k

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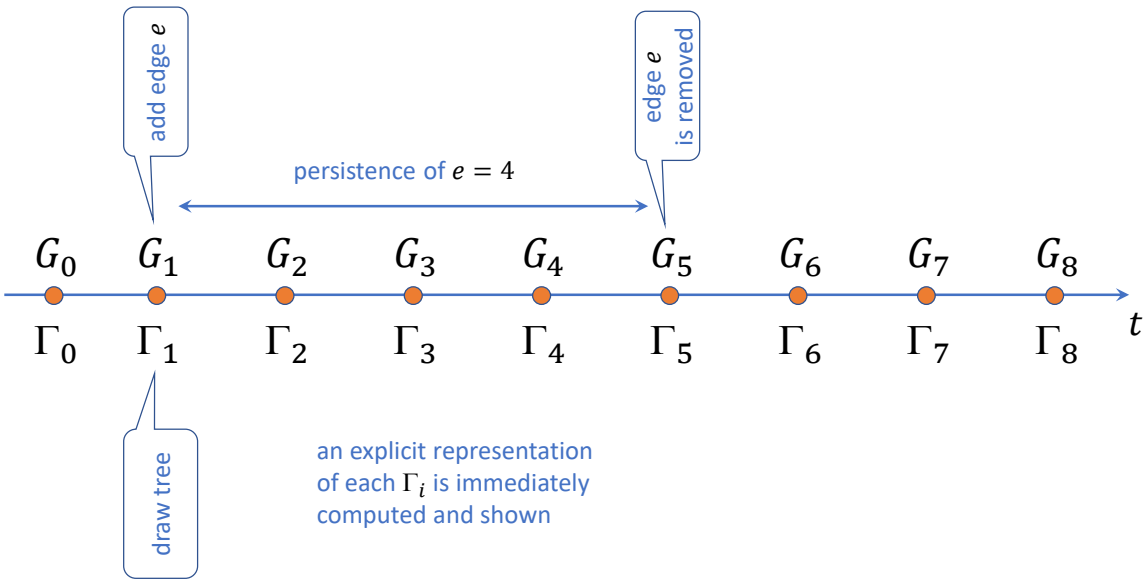
Streaming GD – a drawing story of a tree story



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Selected contributions

- Binucci Brandes gdb Didimo Gaertler Palladino Patrignani Symvonis Zweig, Drawing trees in a streaming model, GD 2009
- Nguyen Eades Hong, Streameb: Stream edge bundling, GD 2012
- Goodrich Pszona, Streamed graph drawing and the file maintenance problem, GD 2013
- Crnovrsanin Chu Ma, An Incremental Layout Method for Visualizing Online Dynamic Graphs, GD2015

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Some Results

Graph story	Drawing story	Objects	Memory	Update time	Number of points in convex position
Degree d Trees (Eulerian Tour only)	planar straight-line, circular layout	edges	$O(k)$	$O(k)$	$\left\lceil \frac{k}{2} \right\rceil (d-1)+k+1$
Trees (Eulerian Tour only)	planar straight-line, circular layout	edges	$O(k)$	$O(k)$	$2k-1$

k is the persistence (size of the window)

target: *reuse* the area

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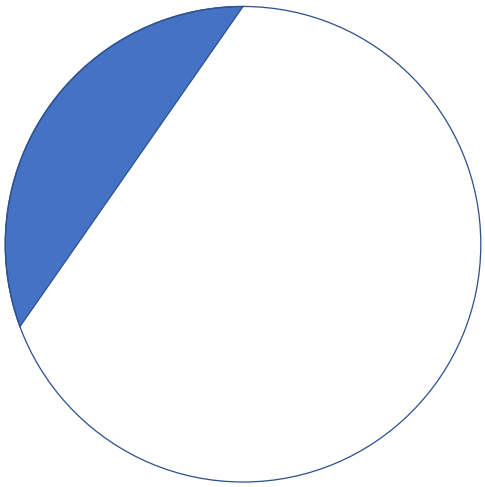
Methods – the art of reusing the space



Evolution of the drawing during the Eulerian tour of the tree

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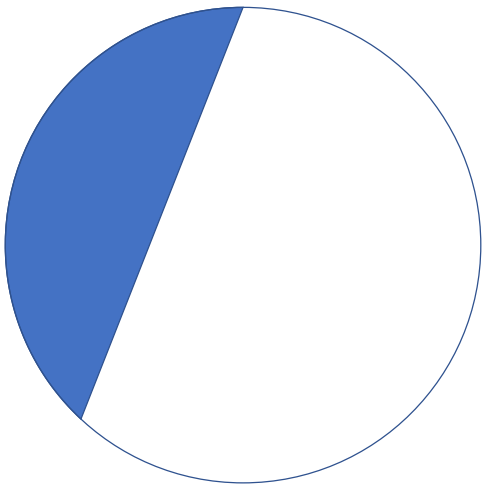

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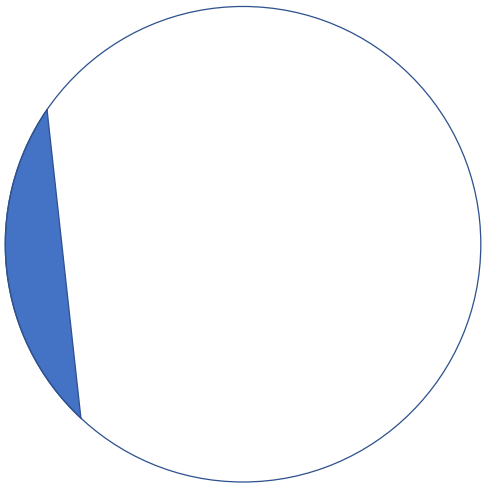

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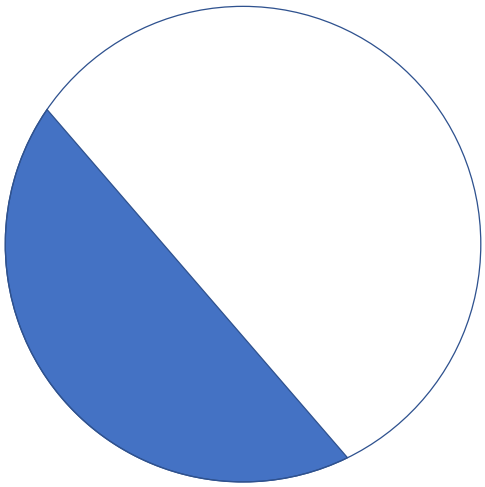

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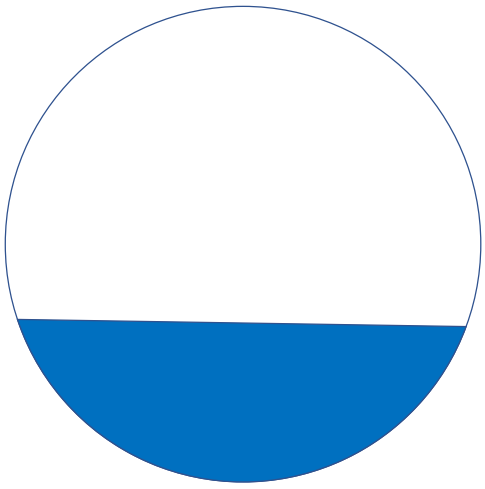

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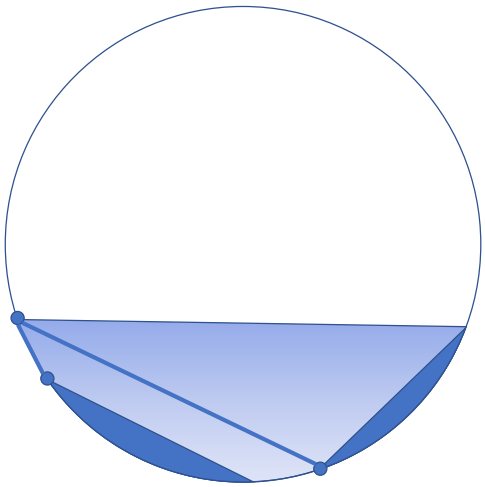

Evolution of the drawing during the Eulerian tour of the tree

Eulerian tour = DFS + explicit backtrack edges

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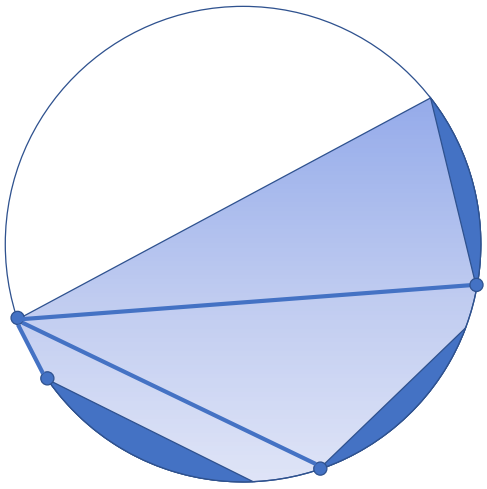
Methods – the art of reusing the space



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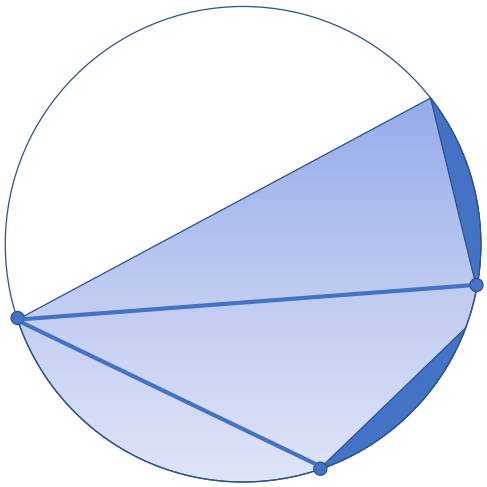

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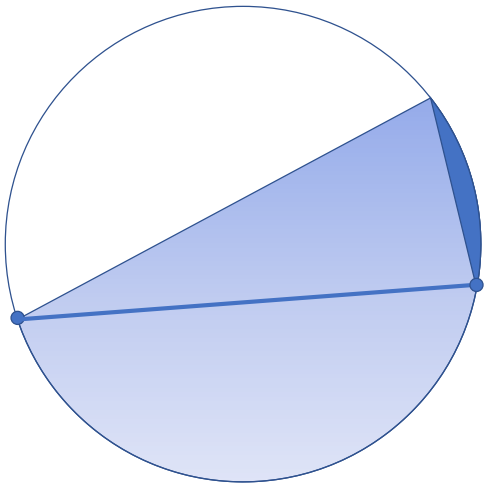

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Eulerian tour = DFS + explicit backtrack edges

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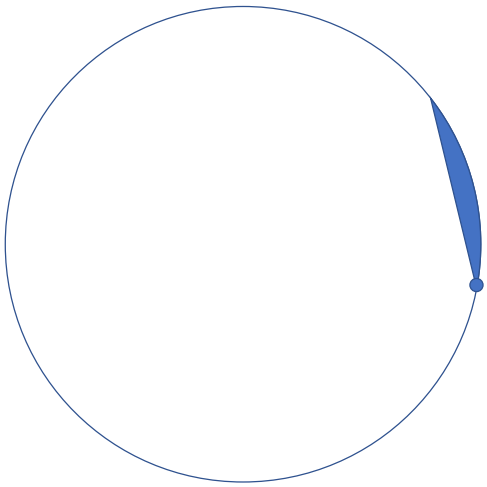

Evolution of the drawing during the Eulerian tour of the tree

Eulerian tour = DFS + explicit backtrack edges

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If we use dynamic graph drawing for streaming

Graph story	Drawing story	Objects	Memory	Update time	Number of points in convex position (streaming)	Area
Trees (Eulerian Tour)	planar straight-line, circular layout	edges	$O(k)$ $O(k)$	$O(k)$ $O(k)$	$2k-1$	$O(k^3)$ $O(k^2)$

k is the persistence (size of the window)
Dynamic graph drawing bound

So what? In dynamic graph drawing the objects *move*, even of a linear amount of space for just one update

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Streaming – problems

- Non-tree stories
- Non-Eulerian-tour visit
- Explore the area-movement tradeoff, following the developments in Goodrich Pszona GD2013

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Offline - animation

	Animation	Timeline
Offline		
Online		

All the updates are known in advance

The graphs of the resulting sequence are drawn one-after-the-other so that the mental map is preserved

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Selected contributions

- Brandes Wagner, Dynamic grid embedding with few bends and changes, ISAAC 1998
- Diehl Görg, Graphs, they are changing, GD 2002
- Erten Harding Kobourov Wampler Yee, Graphael: Graph animations with evolving layouts, GD 2003
- Brandes Fleischer Puppe, Dynamic spectral layout with an application to small worlds, JGAA 2007
- Da Lozzo Rutter, Planarity of streamed graphs, CIAC 2015
- Skambath Tantau, Offline drawing of dynamic trees: Algorithmics and document integration, GD 2016
- *Borrazzo Da Lozzo Frati Patrignani, Graph Stories in Small Area, GD 2019*

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Radian

- Candela Di Bartolomeo gdb Squarcella, Radian: Visual Exploration of Traceroutes, TVCG 2018
- Application of clustered planarity techniques
- available at http://www.dia.uniroma3.it/~compunet/projects/radian/

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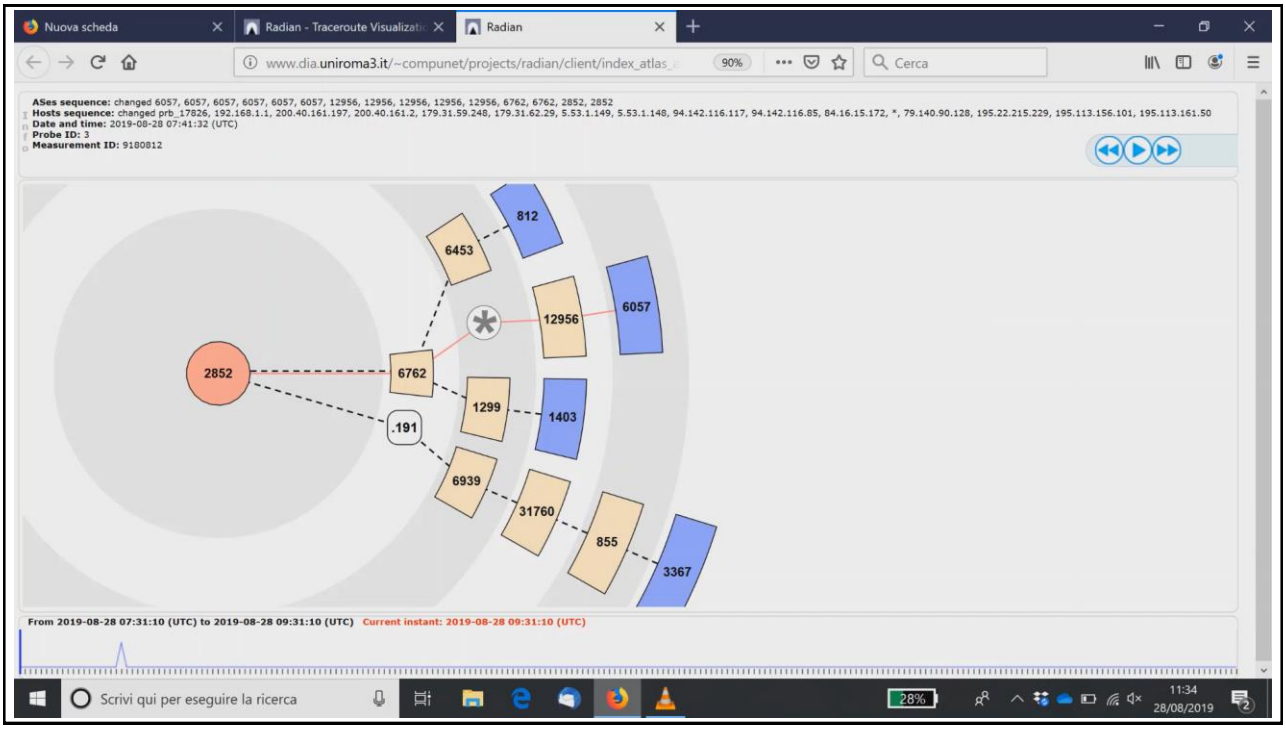

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Radian Methods

- Augment clusters
  - Add vertices and edges into clusters so that every path traversing a cluster c has the same number of vertices in c
- Assign layers
  - Compute a layering for all vertices
- PQ-tree layout
  - Use a PQ-tree to order vertices along the layers so that (1) vertices on a layer and belonging to the same cluster are consecutive and (2) the number of edge crossings is low
  - The PQ-tree is initialized with a spanning tree of the graph and is incrementally updated with the remaining edges, which induce ordering constraints

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Offline animation – problems

- In some problems it is difficult or impossible to maintain certain invariants of the drawing
  - *Temporal cuts* can be introduced (see Skambath Tantau 2016) when some invariants are violated and the drawing is "reset"
  - Look for drawing stories with few temporal cuts

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Storyline & C.

	Animation	Timeline
Offline		Storyline & C.
Online		

One Cartesian coordinate represents time

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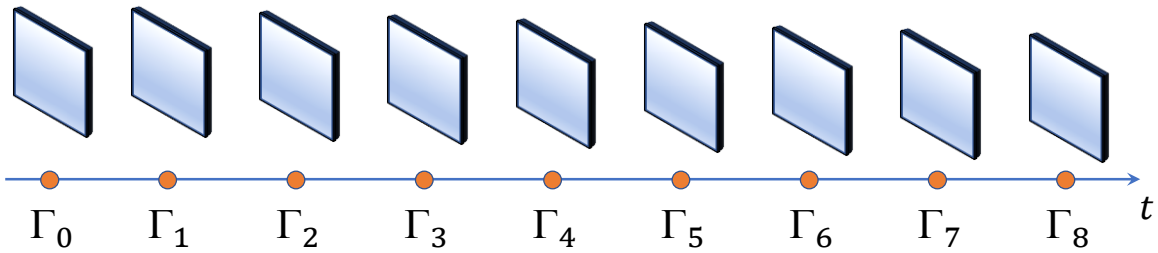
Timeline representation – an example

- All the Γ_i are *together* in the drawing



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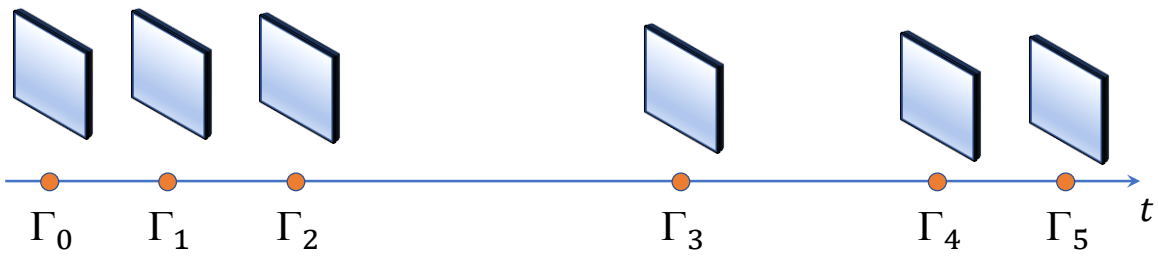
Timeline representation – deformation of time

Wang Archambault Haleem Moeller Wu Qu, Nonuniform Timeslicing of Dynamic Graphs Based on Visual Complexity, VIS 2019



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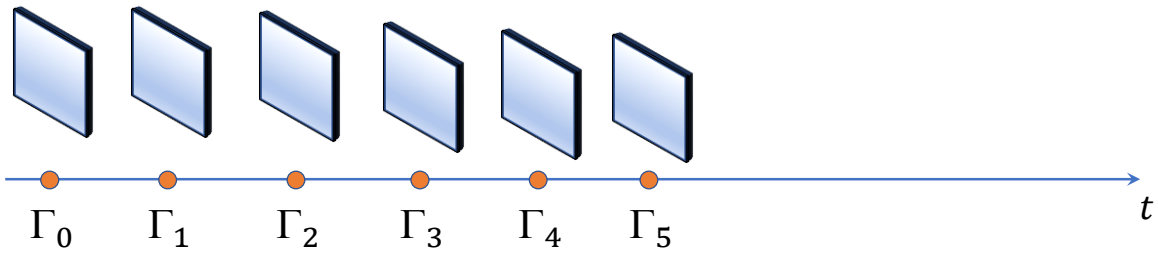

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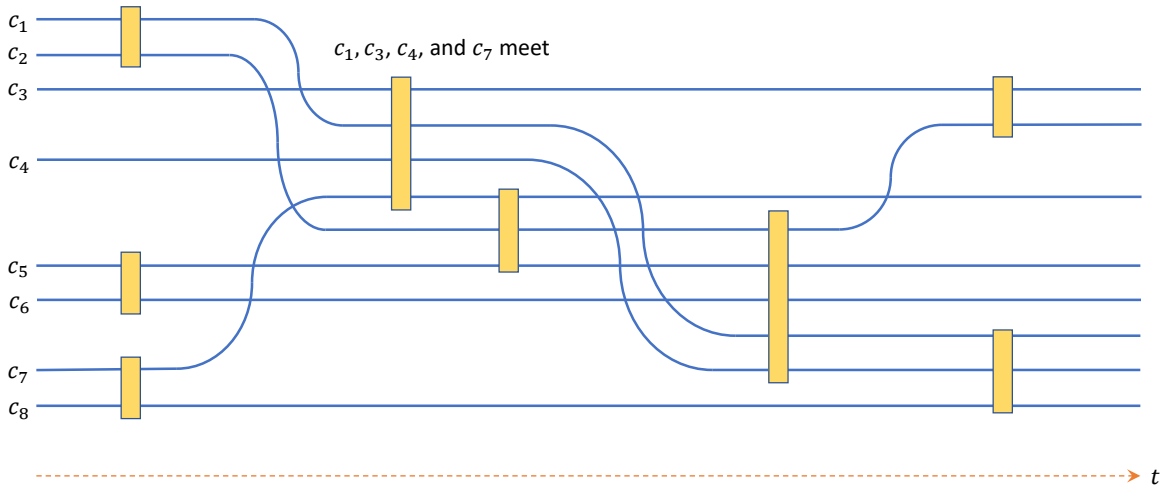
Storyline - abstraction of the structure of a narrative



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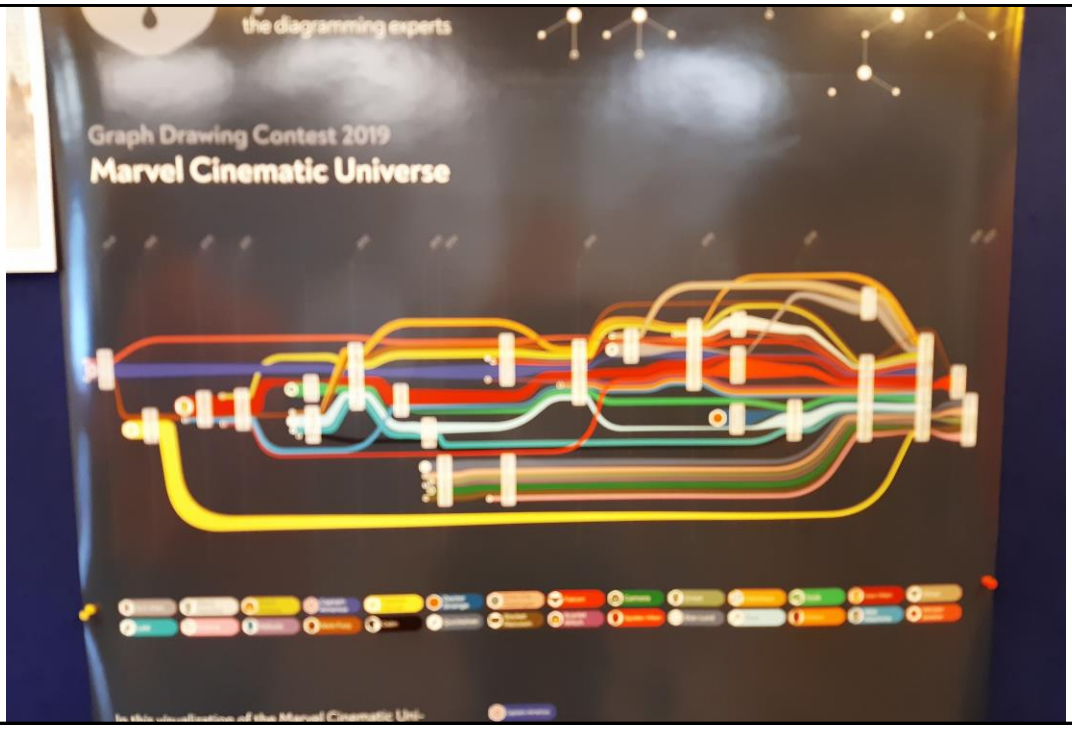

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Goals and Methods

- Minimize crossings between characters
- Minimize crossings between bundles of characters (block crossings)

- Exact algorithms
- Integer Linear Programming
- SAT solvers

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Selected contributions

- Tanahashi Ma, Design Considerations for Optimizing Storyline Visualizations, TVCG 2012
- Kostitsyna Nöllenburg Polishchuk Schulz Strash, On minimizing crossings in storyline visualizations, GD 2015
- van Dijk Fink Fischer Lipp Markfelder Ravsky Suri Wolff, Block crossings in storyline visualizations, GD 2016
- Gronemann Jünger Liers Mambelli, Crossing minimization in storyline visualization, GD 2016
- van Dijk Lipp Markfelder Wolff, Computing storyline visualizations with few block crossings, GD 2017

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Upstream visibility

- Candela gdb Marzialetti, Upstream Visibility: A Multi-View Routing Visualization, VINCI 2018

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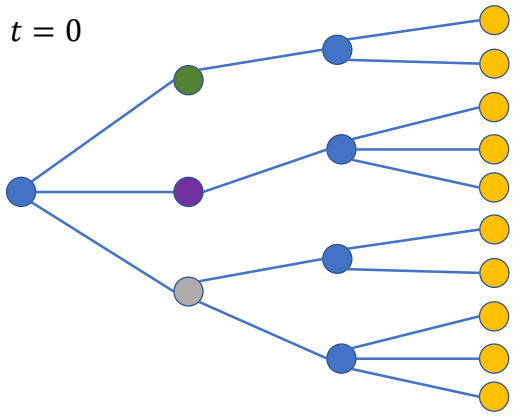
A streamgraph paradigm for routing visualization



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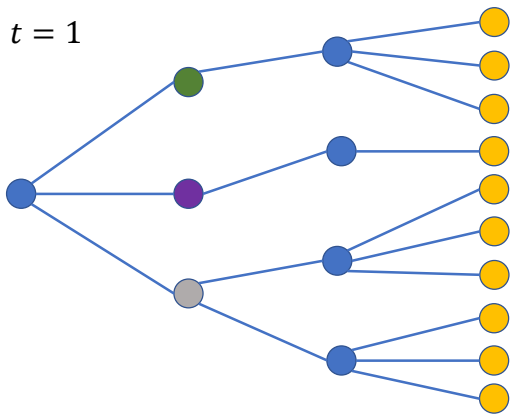

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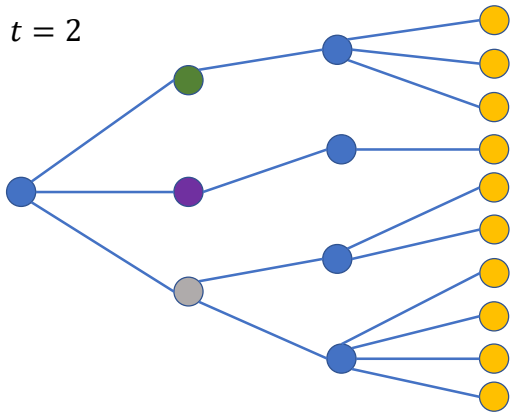

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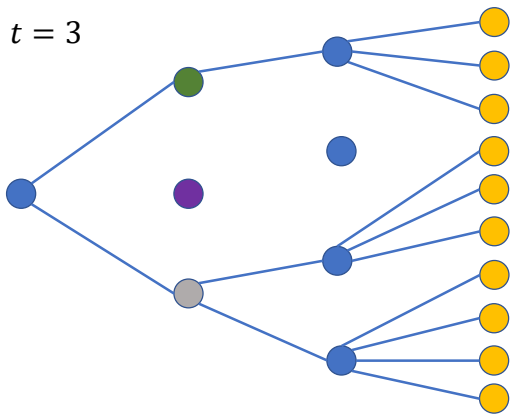

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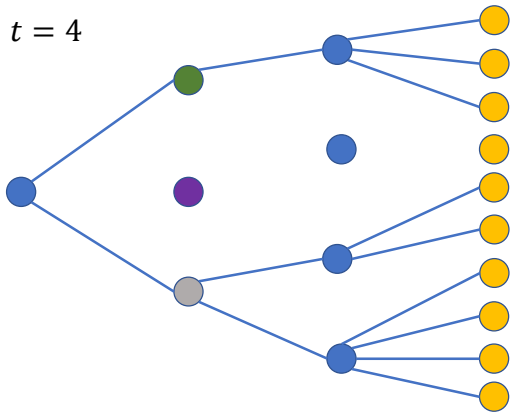

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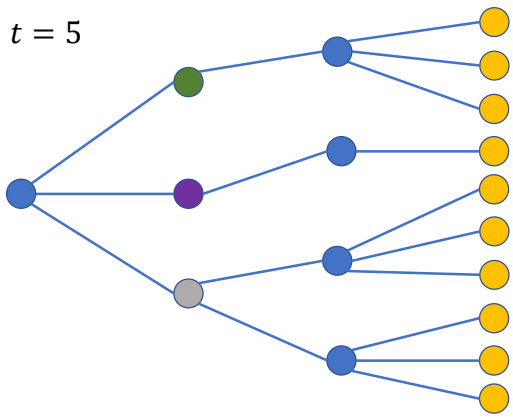

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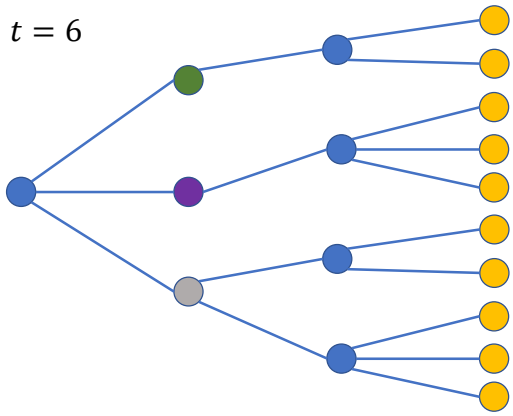

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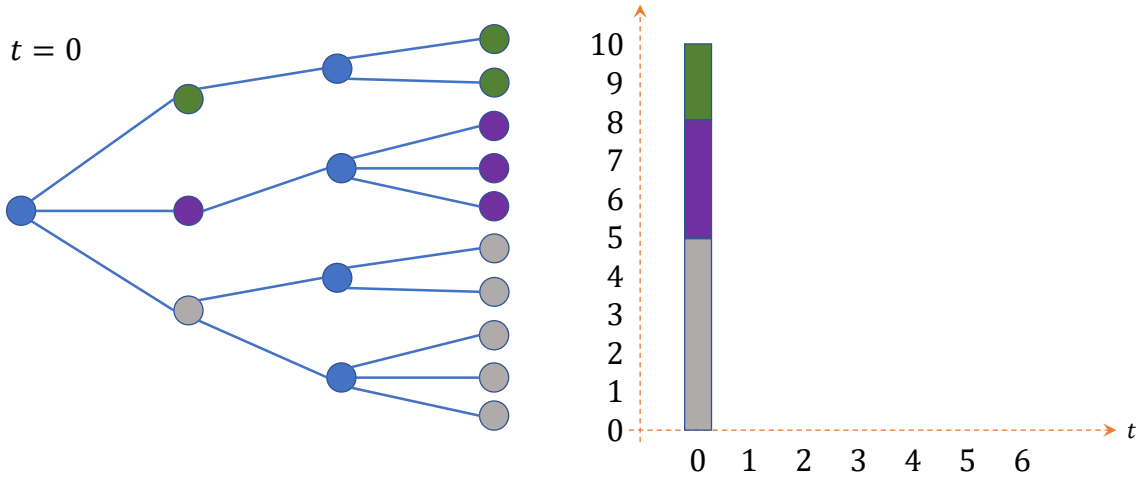

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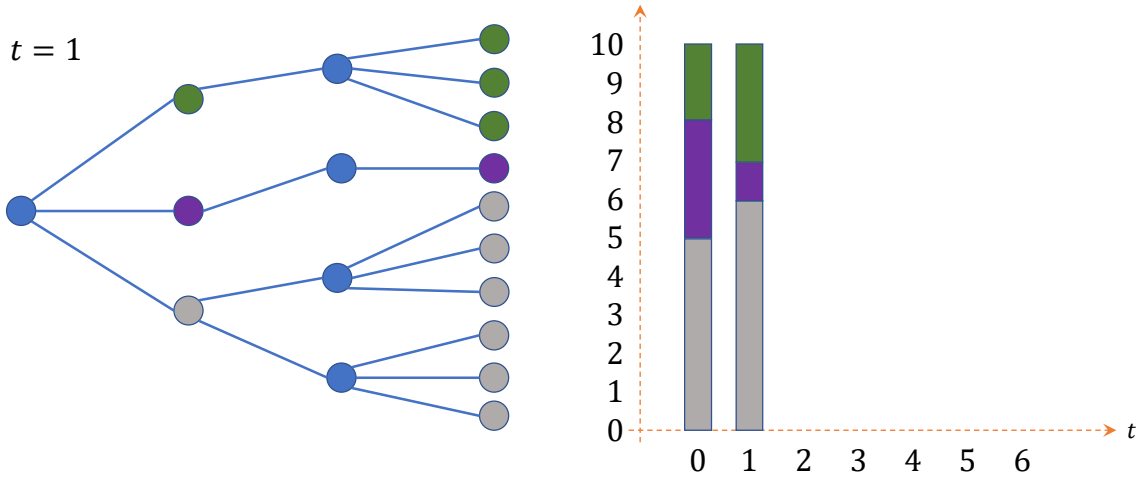

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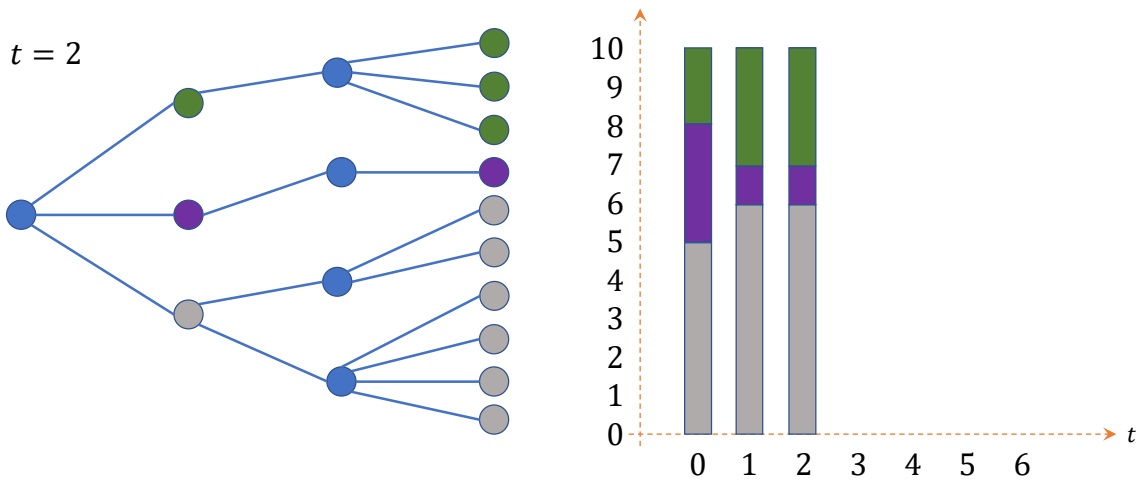

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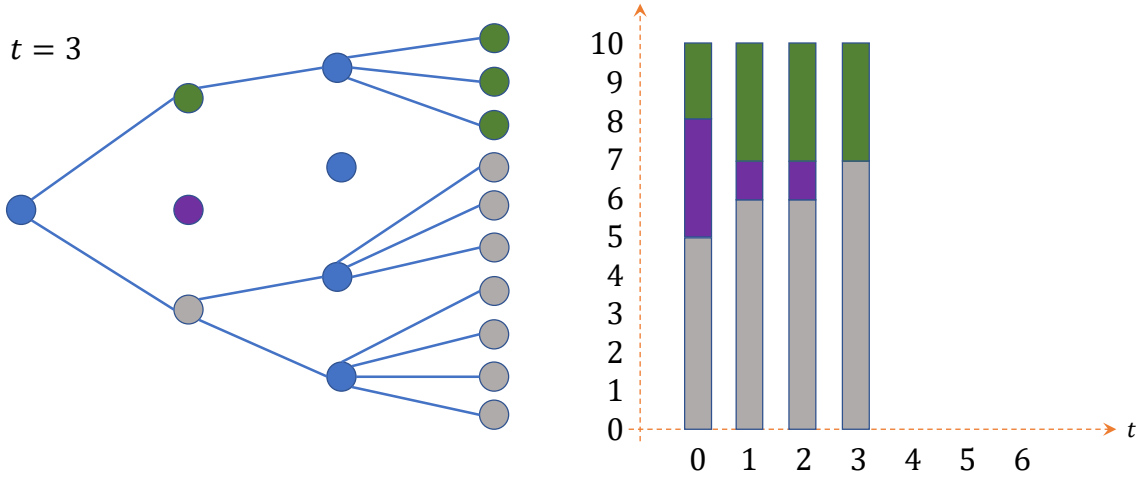

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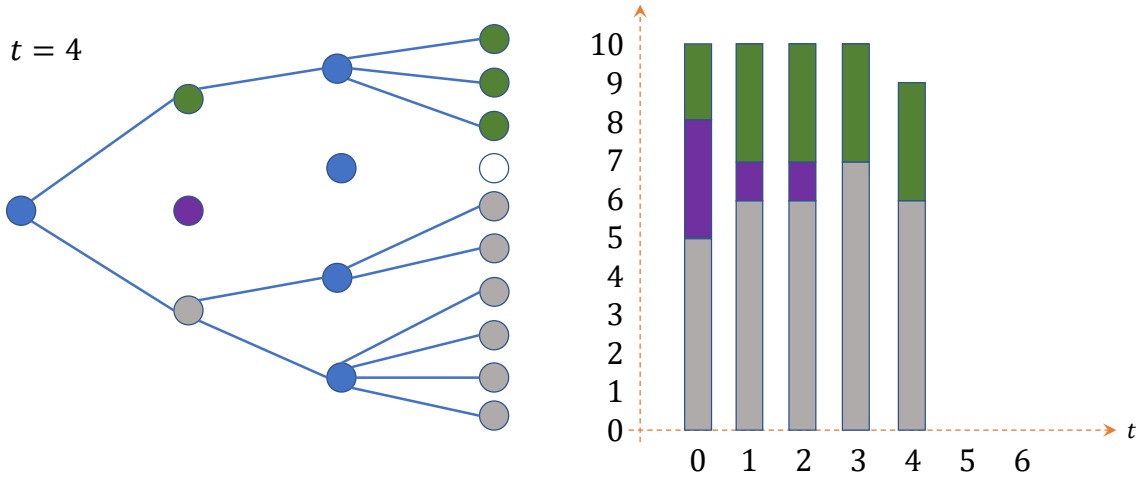

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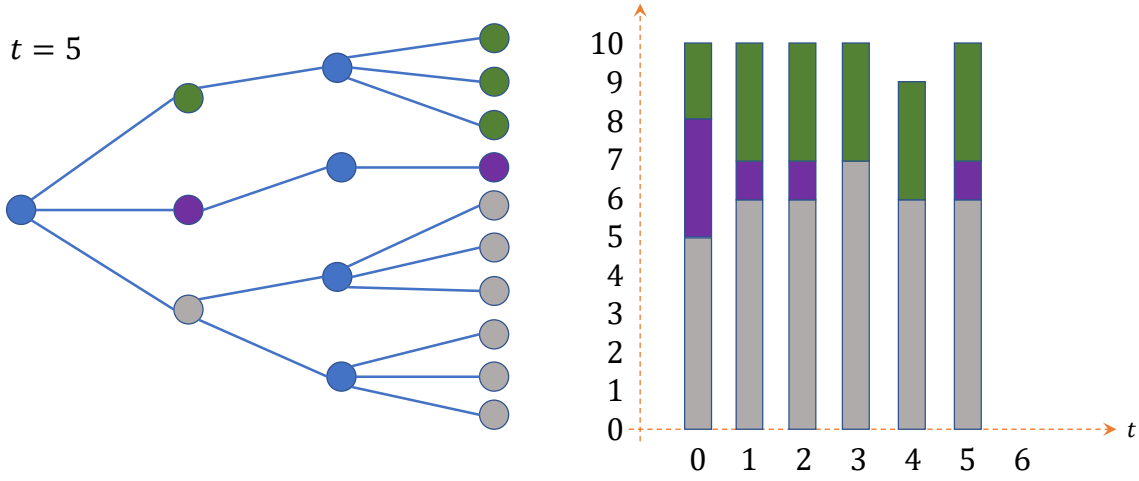

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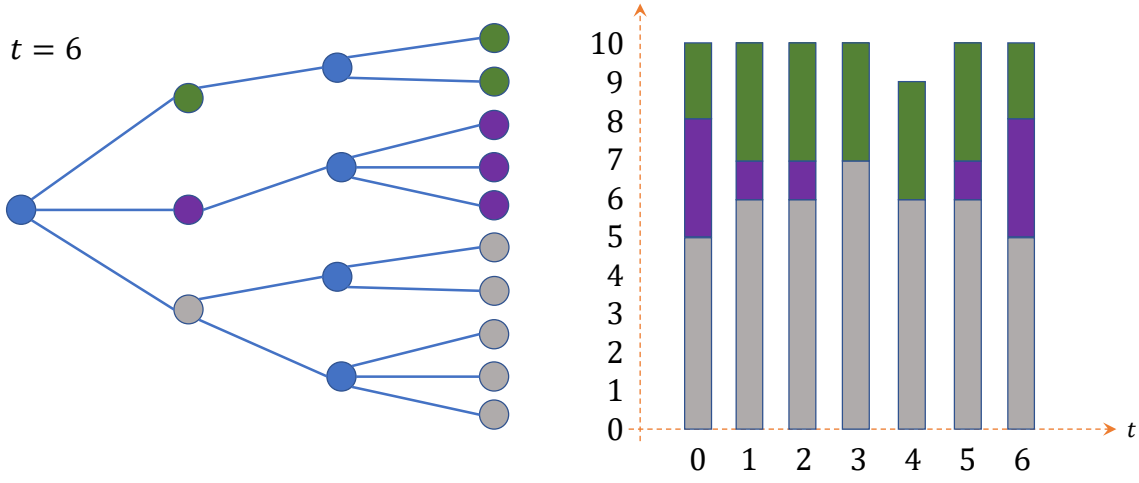

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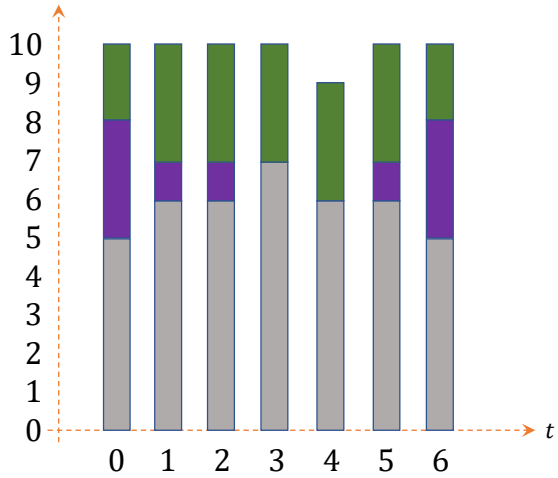

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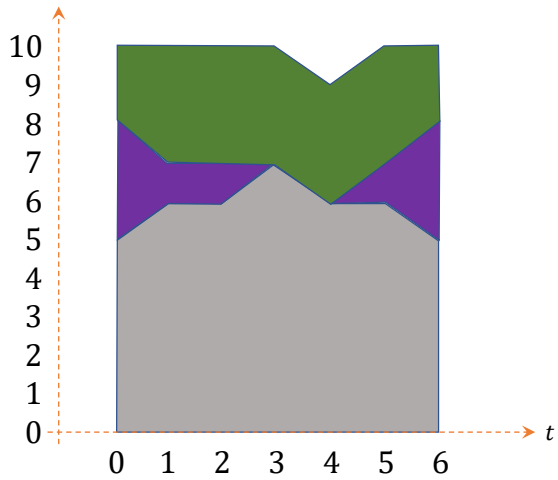
A routing streamgraph

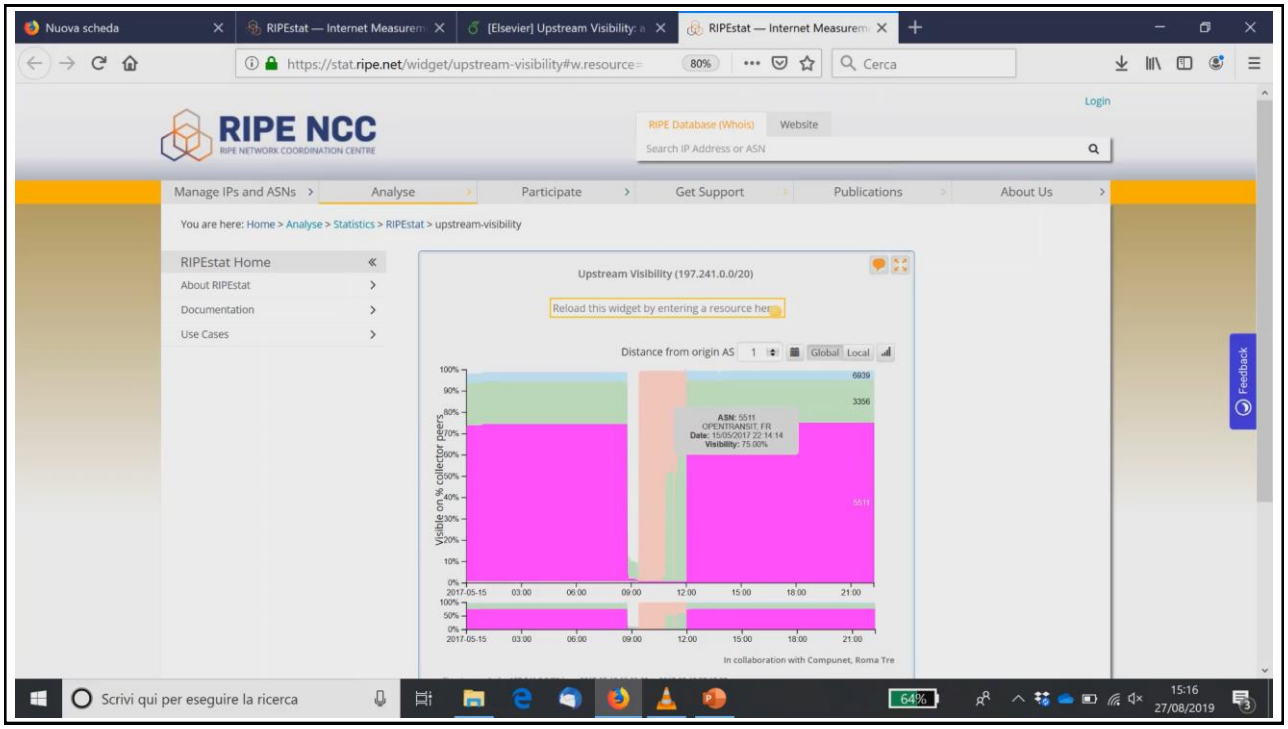


64

Upstream Visibility **clip**

- service available at RIPE Stat

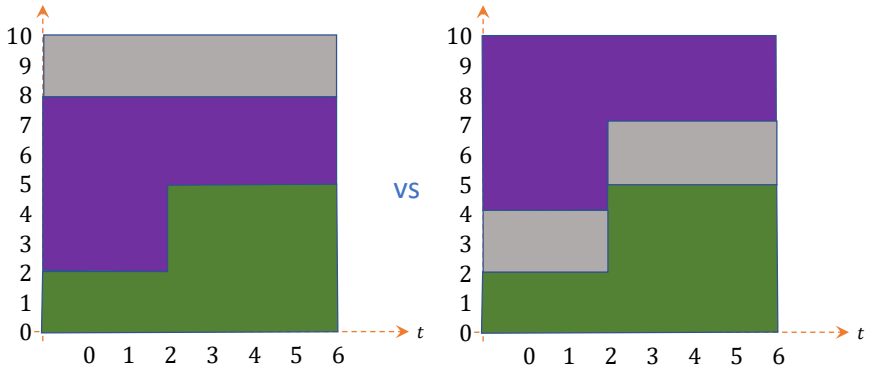
65



66

Streamgraph – problems

- Find an ordering of the curves so that each colored region is «smooth»



See also: Di Bartolomeo Hu, There is more to streamgraphs than movies: Better aesthetics via ordering and lassoing, Computer Graphics Forum 2016

67

Timeline representations – problems

- How to visualize a graph story according two or more clocks?
  - Physical quantity clock
  - Event clock
  - ….
- Lotker, The tale of two clocks, IEEE/ACM ASONAM 2016
  - using the drift between clocks is useful to understand the dynamics in social networks

68

Morphs

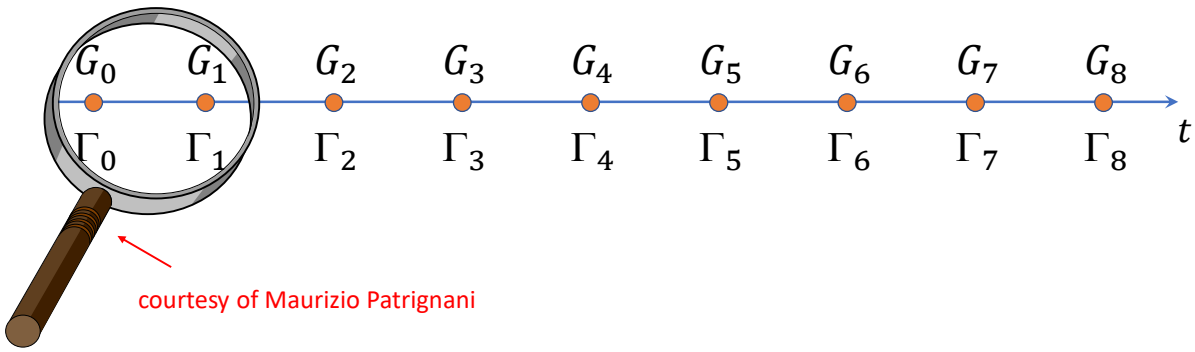
	Animation	Timeline
Offline	Morphs	
Online		

How to transform Γ_i into Γ_{i+1}

69

A closer look at one of the steps

- Focus on Γ_0 and Γ_1
- In general they are different
- How to transform (morph) one into the other?



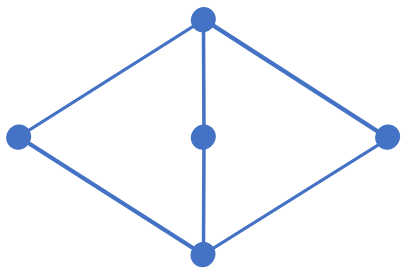
70

The problem of morphing graph drawings

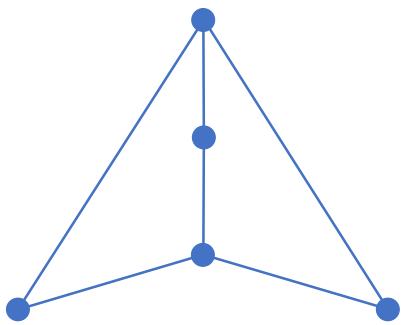
- input: two drawings Γ_0 and Γ_1 of the same graph G
- A *morph* between Γ_0 and Γ_1 is a continuously changing family of drawings of G indexed by time $t \in [0,1]$, such that the drawing at time $t = 0$ is Γ_0 and the drawing at time $t = 1$ is Γ_1

71

A morph



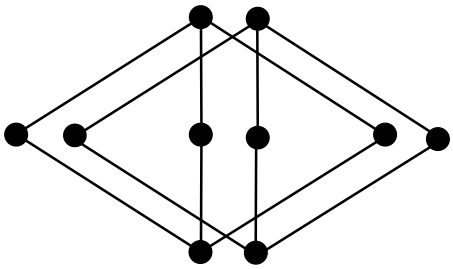
Γ_0



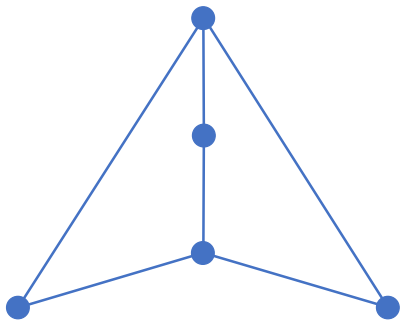
Γ_1

72

A morph



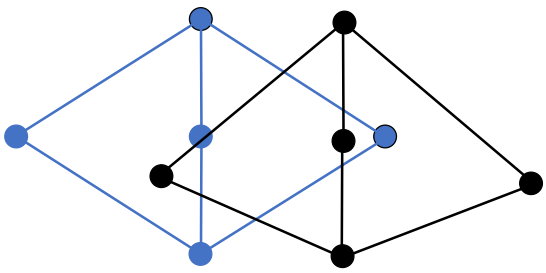
Γ_0



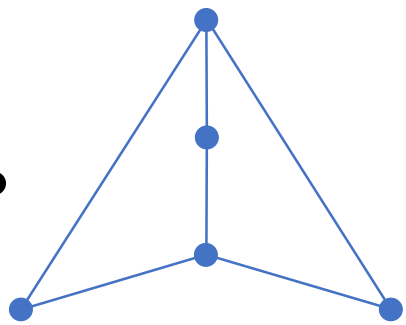
Γ_1

73

A morph



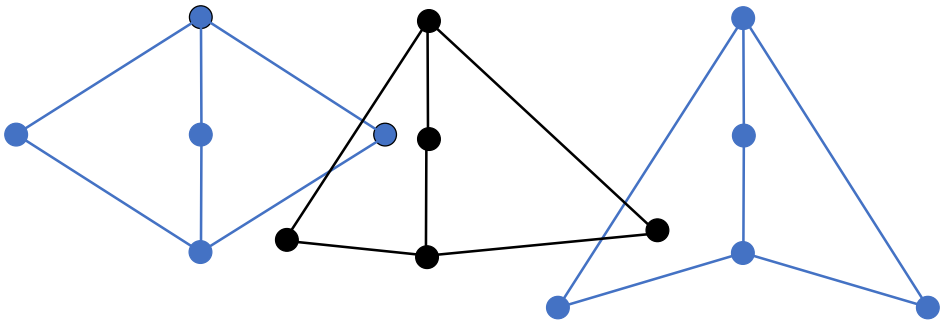
Γ_0



Γ_1

74

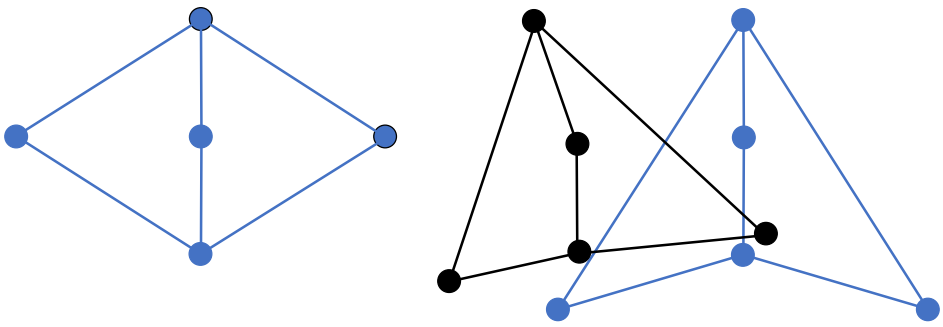
A morph



Γ_0 Γ_1

75

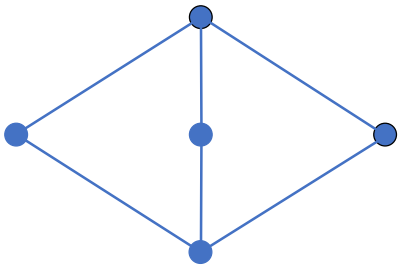
A morph



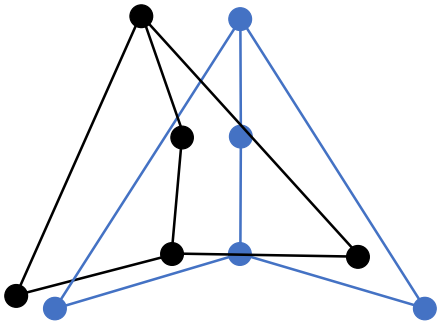
Γ_0 Γ_1

76

A morph



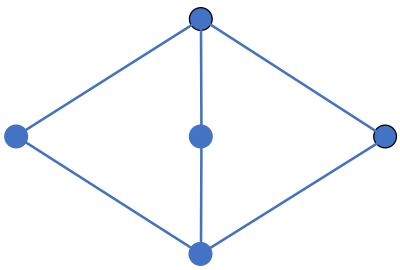
Γ_0



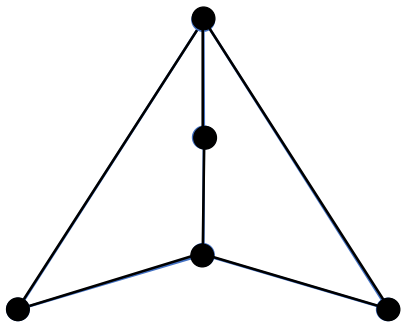
Γ_1

77

A morph



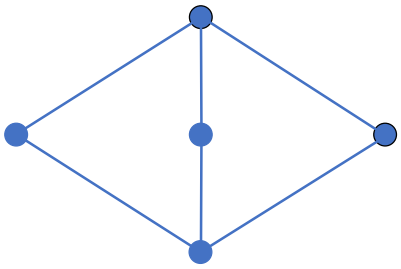
Γ_0



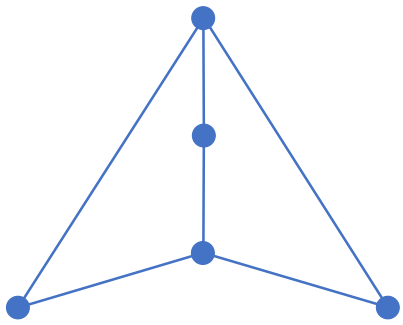
Γ_1

78

A morph



Γ_0



Γ_1

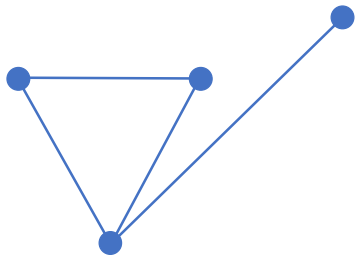
79

Morphing preserving one or more properties

- suppose that both Γ_0 and Γ_1 have a certain geometric property, e.g.
  - they are planar drawings
  - they are straight-line drawings
  - their edges are polygonal lines composed of horizontal and vertical segments
  - their faces are covex polygons
  - ….
- it is interesting that all the drawings of the morph *preserve* that property

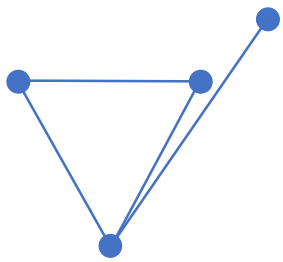
80

A morph that does not preserve planarity



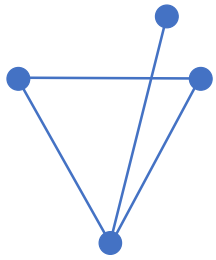
81

A morph that does not preserve planarity



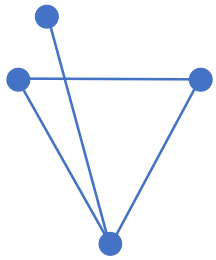
82

A morph that does not preserve planarity



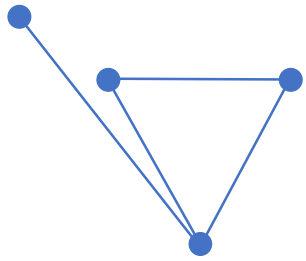
83

A morph that does not preserve planarity



84

A morph that does not preserve planarity

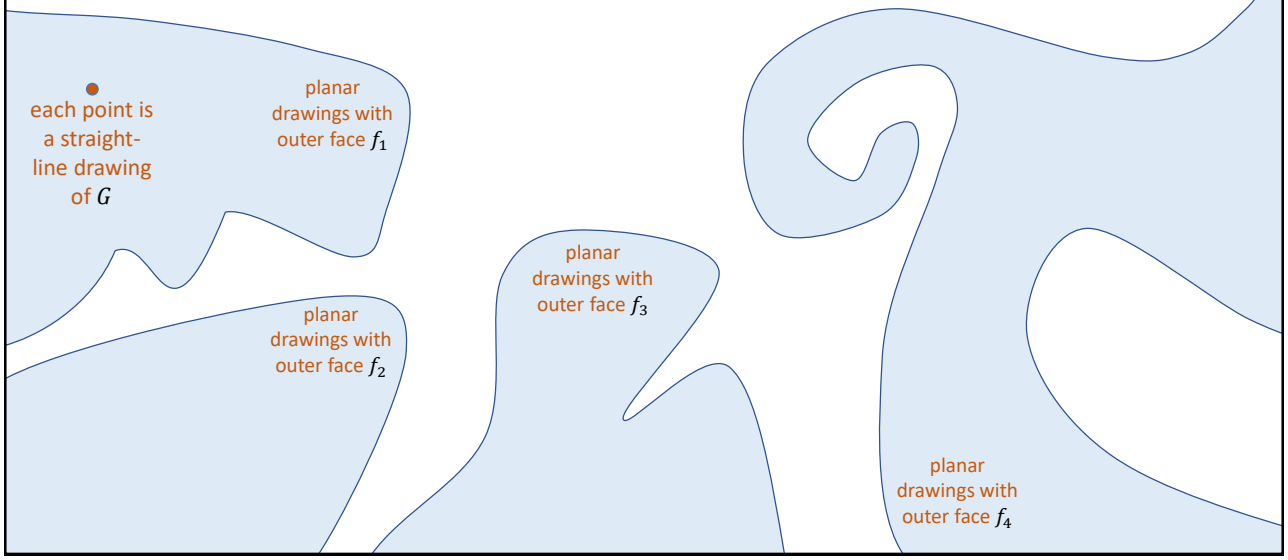


85

morphs
straight-line drawings of triangulations

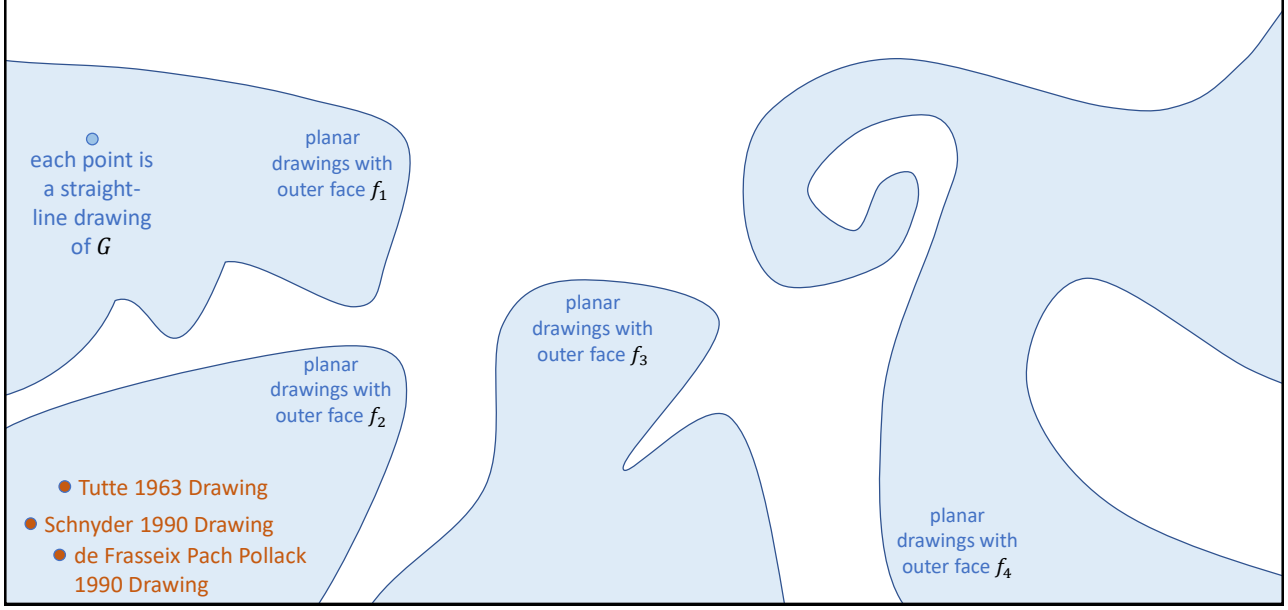
86

Straight-line drawings of a triangulation G with n vertices in R^{2n}



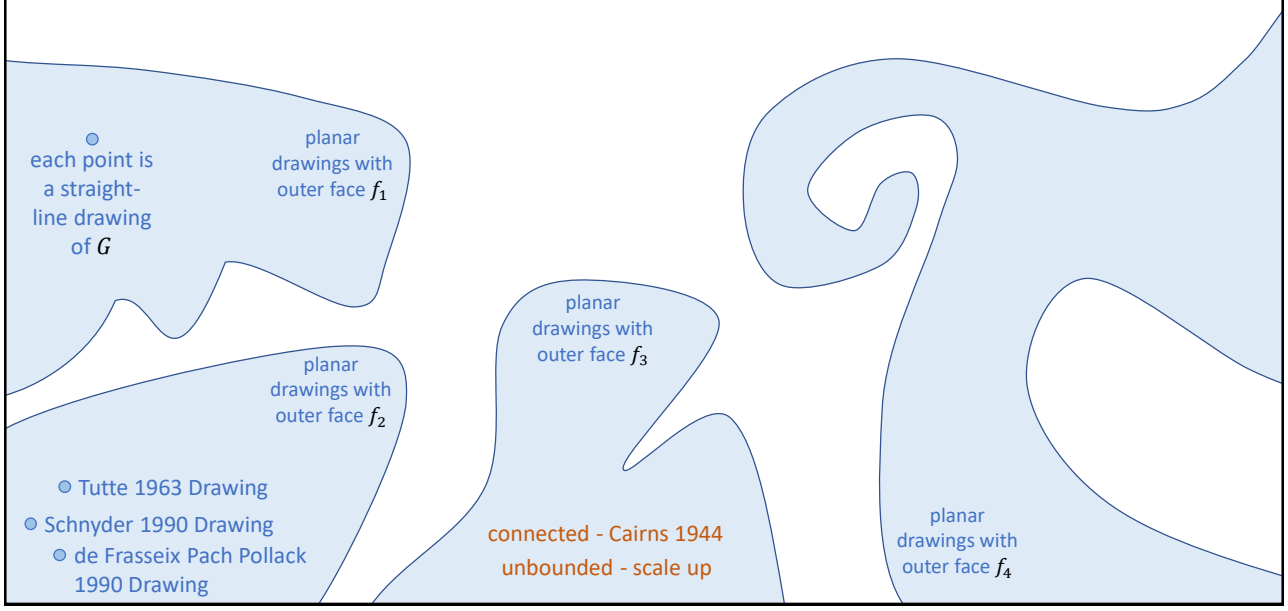
87

Straight-line drawings of a triangulation G with n vertices in R^{2n}



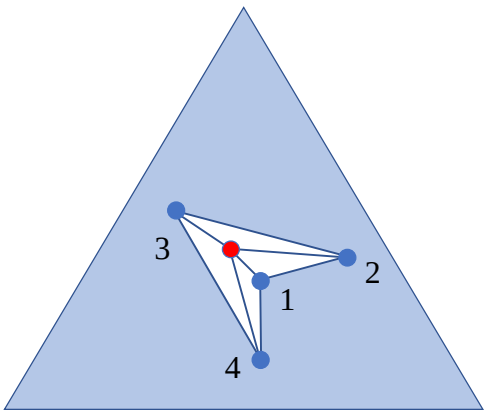
88

Straight-line drawings of a triangulation G with n vertices in R^{2n}

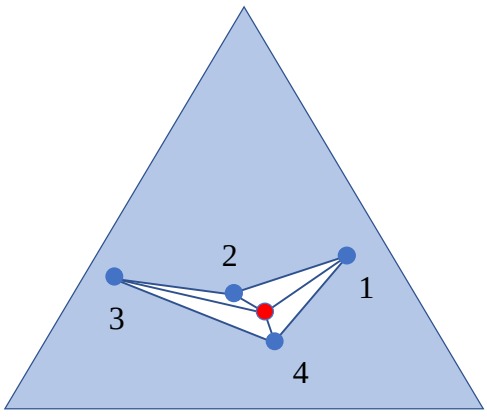


89

Cairn's double recursion approach



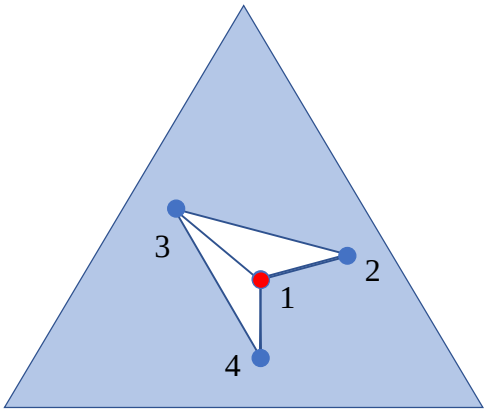
Γ_0



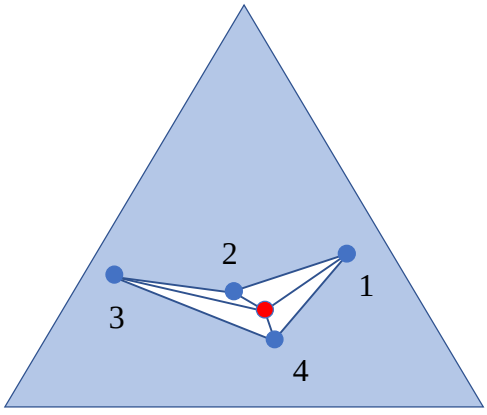
Γ_1

90

Cairn's double recursion approach



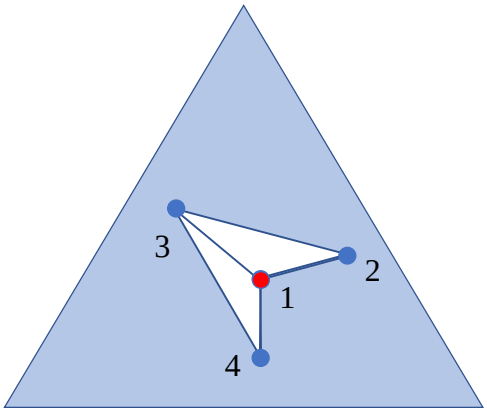
Γ_0



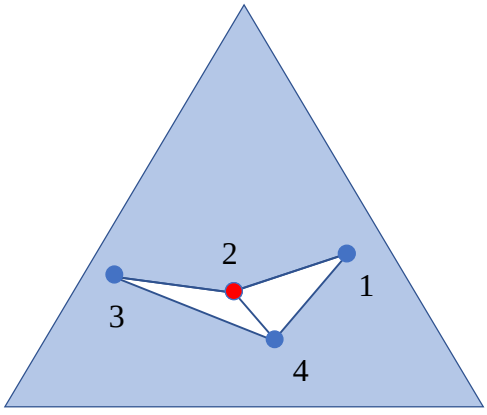
Γ_1

91

Cairn's double recursion approach



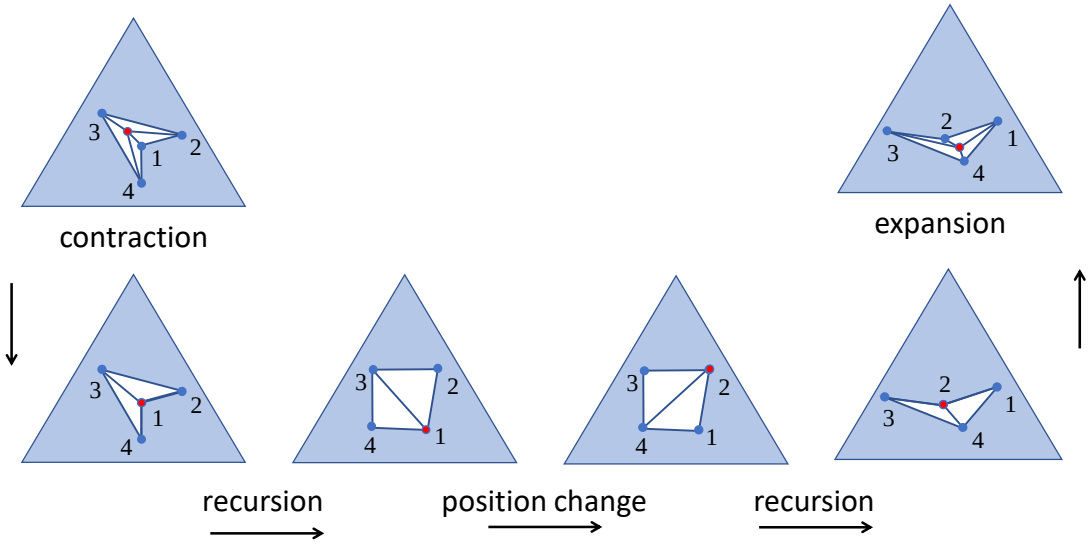
Γ_0



Γ_1

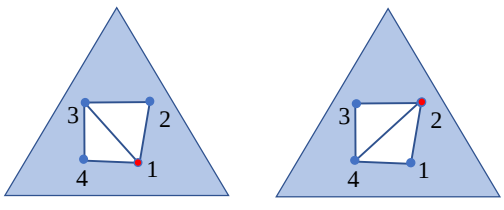
92

Cairn's double recursion approach



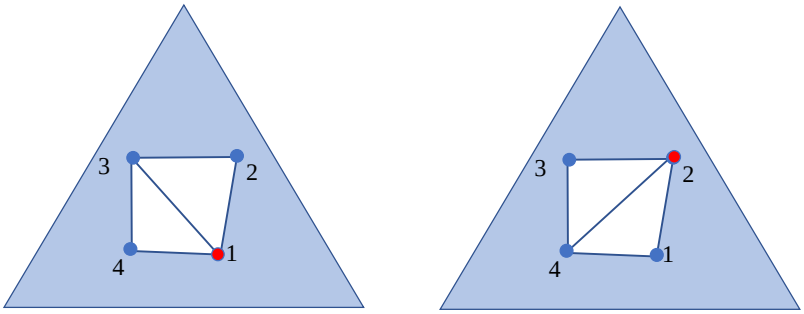
93

A closer look at the position change



94

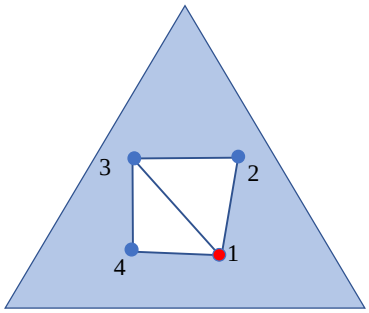
A closer look at the position change



position change

95

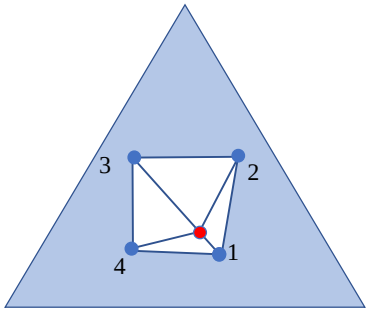
A closer look at the position change



position change

96

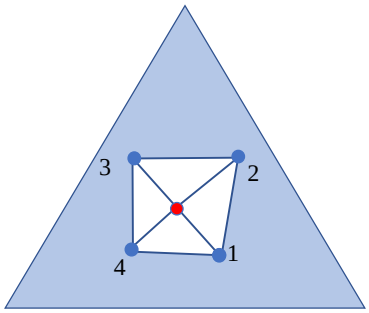
A closer look at the position change



position change

97

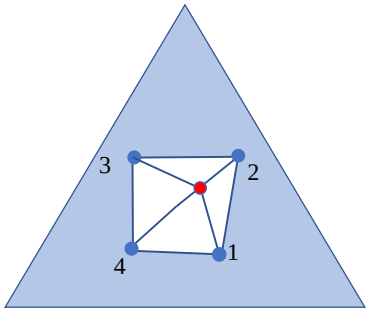
A closer look at the position change



position change

98

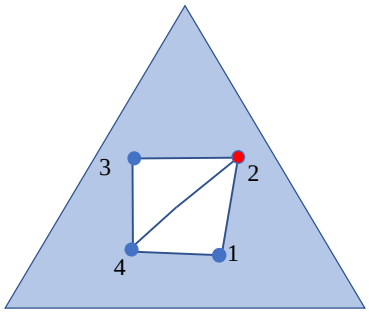
A closer look at the position change



position change

99

A closer look at the position change



position change

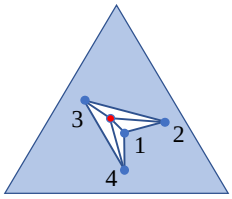
100

Cairn's double recursion approach

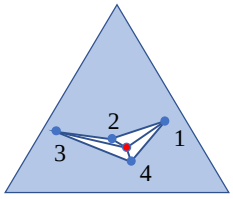
number $S(n)$ of morphing steps

$$S(n) = 2S(n-1) + O(1)$$

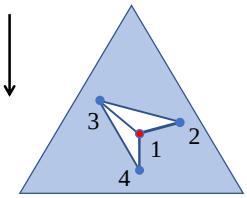
$$S(n) \in O(2^n)$$



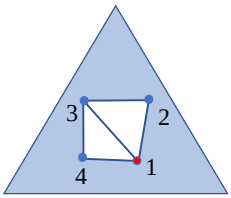
contraction $O(1)$



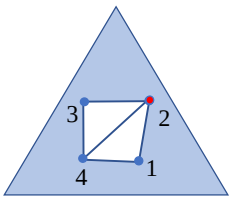
expansion $O(1)$



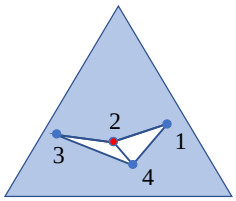
recursion $S(n-1)$



position change $O(1)$

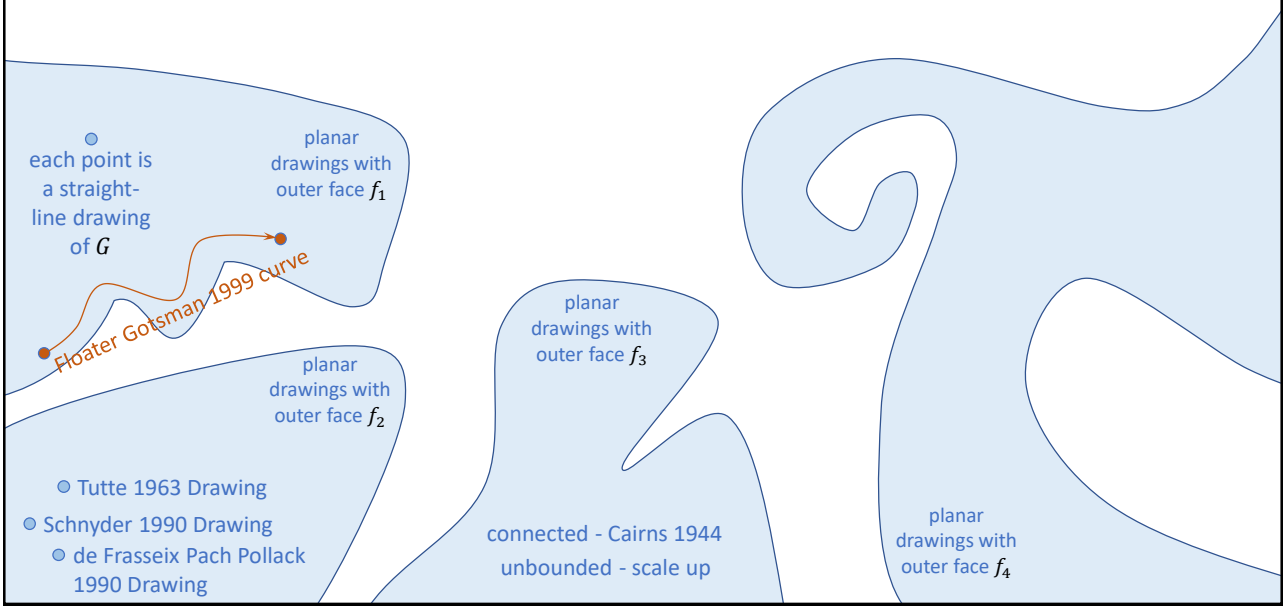


recursion $S(n-1)$



101

Straight-line drawings of a triangulation G with n vertices in R^{2n}



102

Floater Gotsman Curve – outer face

Suppose the outer face has the same drawing in Γ_0 and in Γ_1

103

Floater Gotsman Curve – drawing Γ_0

Determine coefficients $\lambda_{ij}(0)$ such that Γ_0 is a weighted barycentric drawing with weights $\lambda_{ij}(0)$

- Let x_i^0 be the coordinates of vertex i in Γ_0
- Compute positive values $\lambda_{ij}(0)$ so that

$$\sum_{j\in N(i)} \lambda_{ij}(0)\, x_j^0 = x_i^0 \quad \text{and} \quad \sum_{j\in N(i)} \lambda_{ij}(0) = 1$$

104

Floater Gotsman Curve – drawing Γ_1

Determine coefficients $\lambda_{ij}(1)$ such that Γ_1 is a weighted barycentric drawing with weights $\lambda_{ij}(1)$

- Let x_i^1 be the coordinates of vertex i in Γ_1
- Compute positive values $\lambda_{ij}(1)$ so that

$$\sum_{j\in N(i)} \lambda_{ij}(1)\, x_j^1 = x_i^1 \quad \text{and} \quad \sum_{j\in N(i)} \lambda_{ij}(1) = 1$$

105

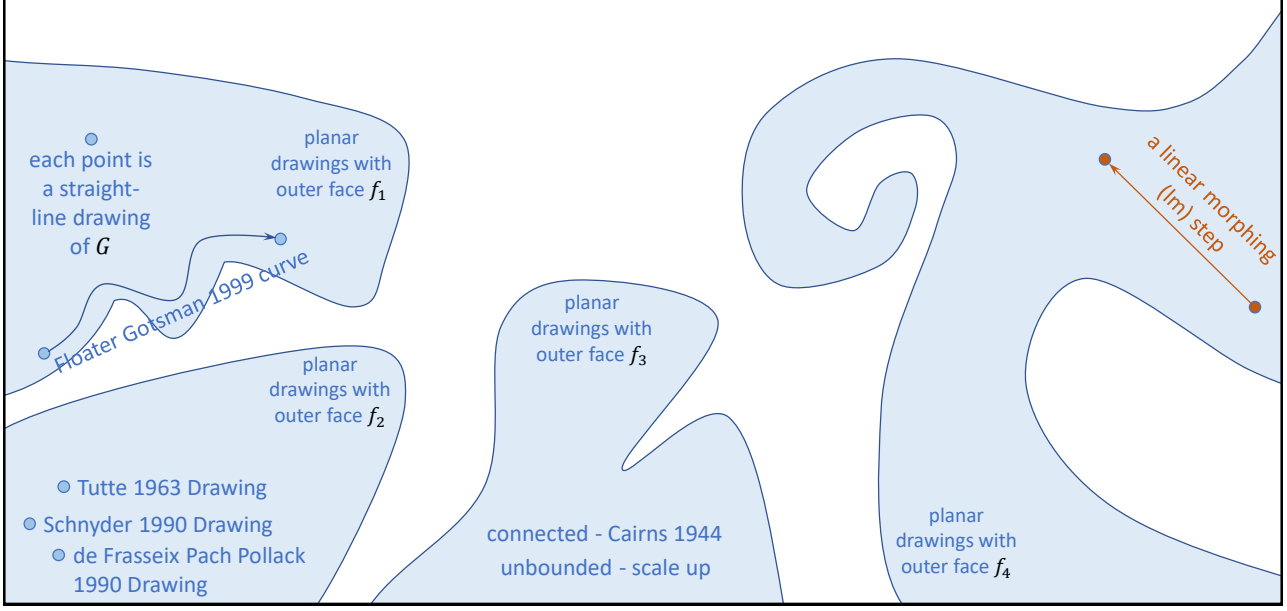
Floater Gotsman Curve

- At each time t, Γ_t is a weighted barycentric (planar) drawing with weights

$$\lambda_{ij}(t) = \lambda_{ij}(0)(1-t) + \lambda_{ij}(1)t$$

106

Straight-line drawings of a triangulation G with n vertices in R^{2n}



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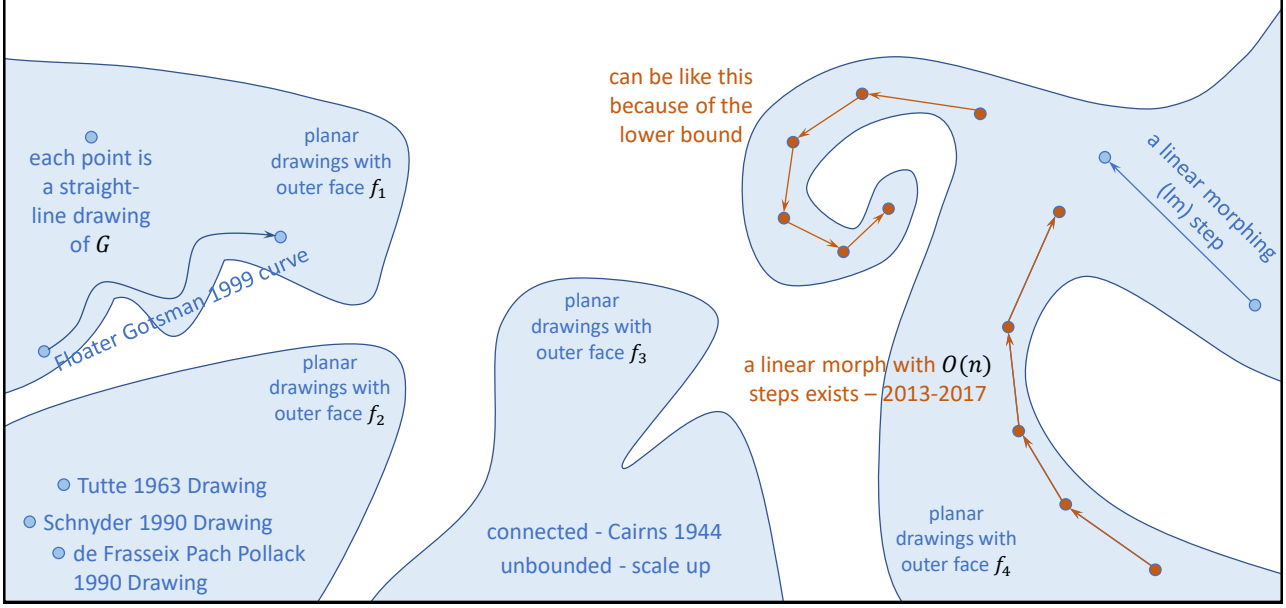
Linear morphs and morphing steps

- In a *linear morphing step* every vertex moves along a straight-line segment at uniform speed
  - Vertices may move at different speeds, and some vertices may remain stationary
- A *linear morph* consists only of linear morphing steps

108

Straight-line drawings of a triangulation G with n vertices in R^{2n}



109

a morph with $O(n)$ lm steps exists – 2013-2017

- S. Alamdari, P. Angelini, T.M. Chan, gdb, F. Frati, A. Lubiw, M. Patrignani, V. Roselli, S. Singla, and B. T. Wilkinson, Morphing planar graph drawings with a polynomial number of steps, SODA 2013
- P. Angelini, F. Frati, M. Patrignani, and V. Roselli, Morphing planar graph drawings Efficiently, GD 2013
- P. Angelini, G. Da Lozzo, gdb, F. Frati, M. Patrignani, and V. Roselli, Morphing planar graph drawings optimally, ICALP 2014
- S. Alamdari, P. Angelini, F. Barrera-Cruz, T.M. Chan, G. Da Lozzo, gdb, F. Frati, P. Haxell, A. Lubiw, M. Patrignani, V. Roselli, S. Singla, B.T. Wilkinson. How to morph planar graph drawings, SICOMP 2017

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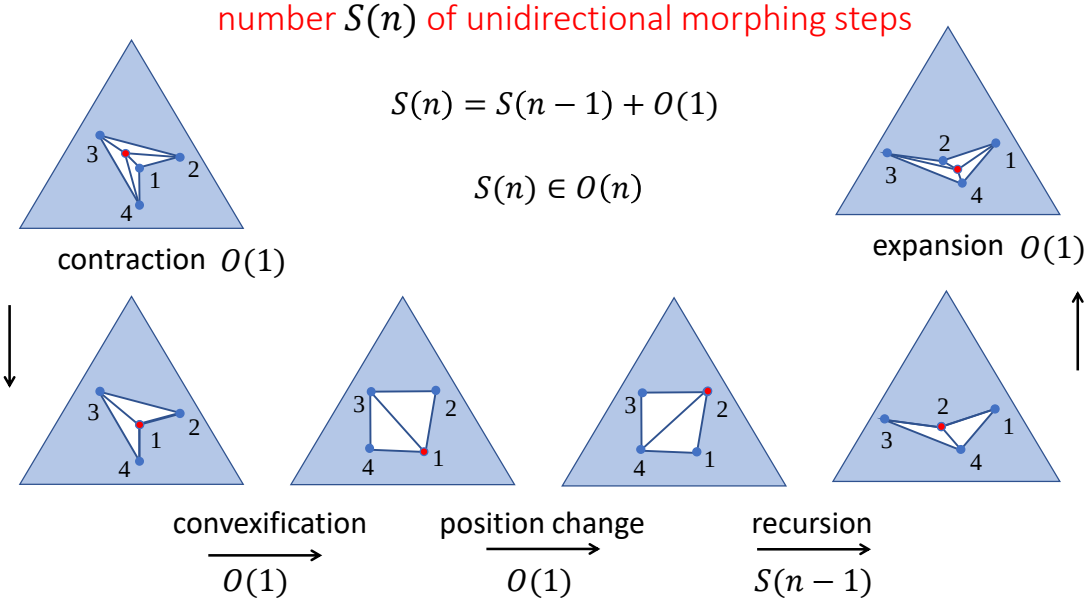
Morphing triangulations with a few steps

number $S(n)$ of unidirectional morphing steps

$S(n) = S(n-1) + O(1)$

$S(n) \in O(n)$



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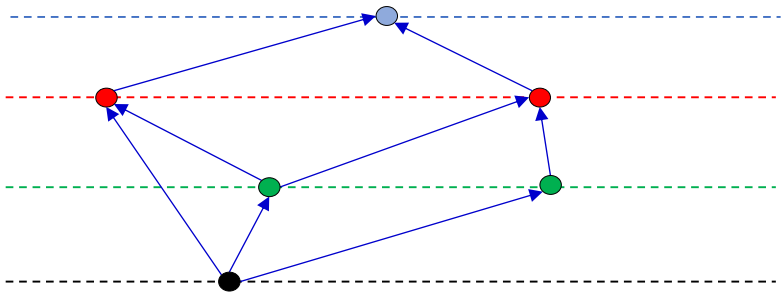
A convexification tool

- Given:
  - a triconnected plane graph $G = (V, E)$
  - a set L of parallel lines
  - a mapping of the vertices of V to lines of L such that orienting the edges of E according to the order of the lines in L yields an st-orientation of G
- Then G admits a convex drawing (all faces are convex polygons) in which each vertex of V lies on the line of L it is mapped to

Hong Nagamochi, Convex drawings of hierarchical planar graphs and clustered planar graphs, JDA 2010

112

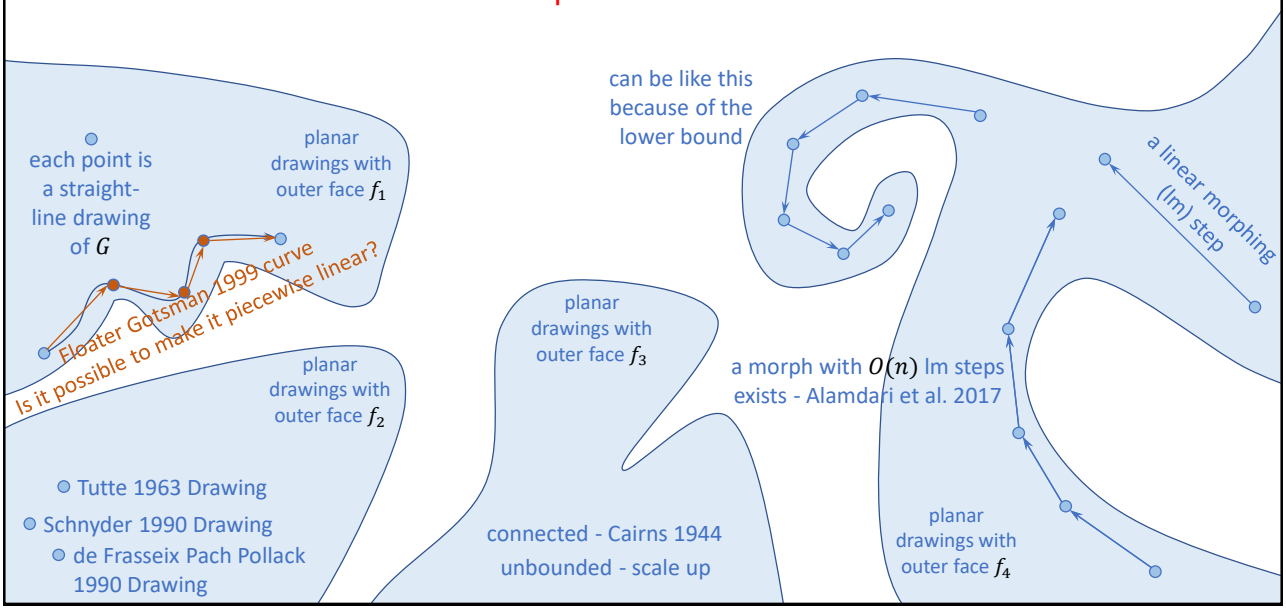
A convexification tool



This slide: Courtesy of Patrizio Angelini

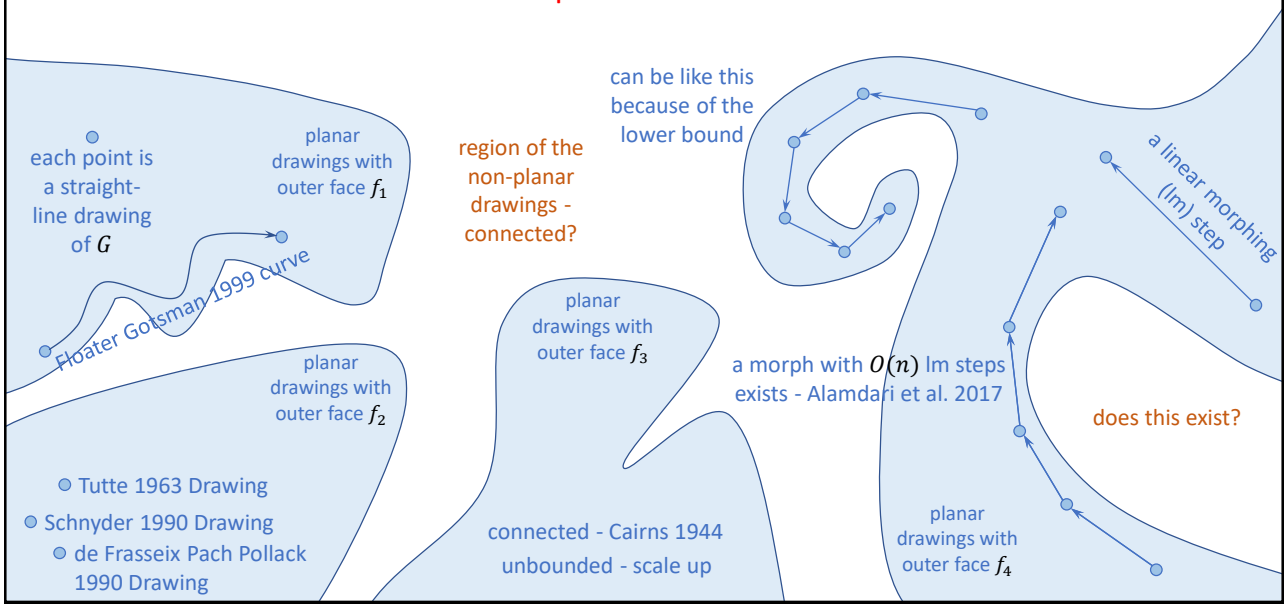
113

Straight-line drawings of a triangulation G with n vertices in R^{2n} problems



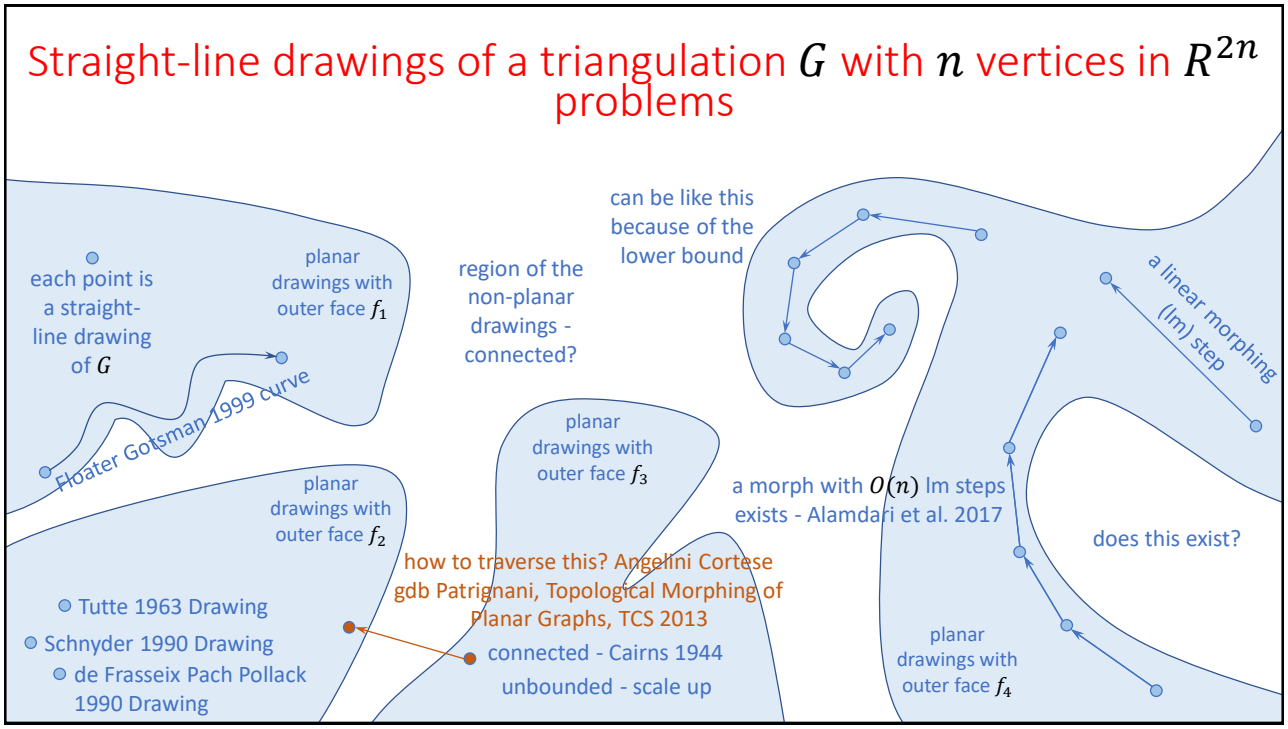
114

Straight-line drawings of a triangulation G with n vertices in R^{2n} problems



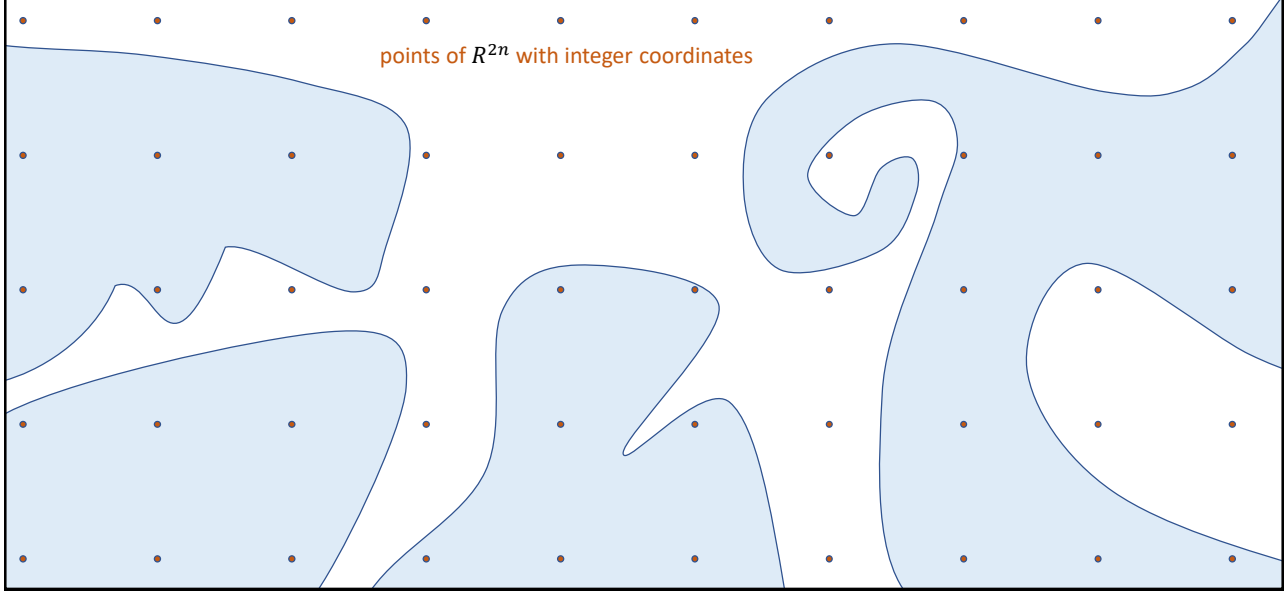
115

Straight-line drawings of a triangulation G with n vertices in R^{2n} problems



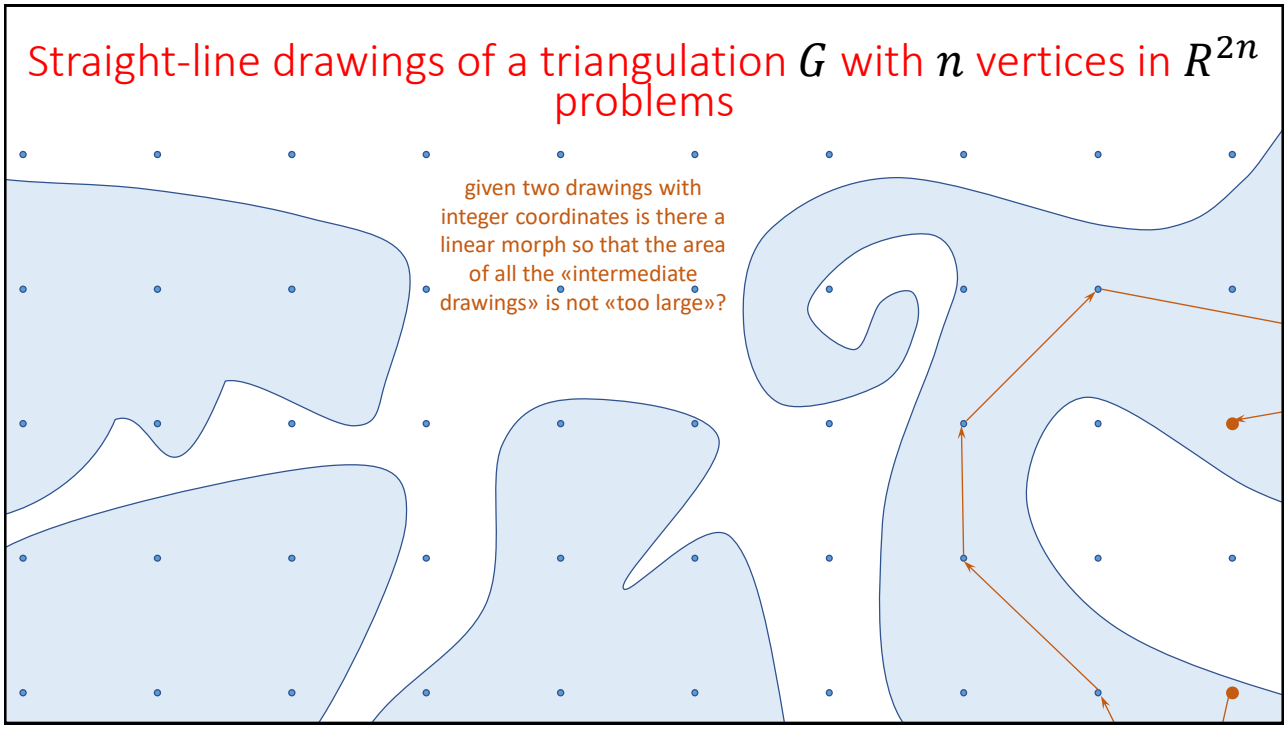
116

Straight-line drawings of a triangulation G with n vertices in R^{2n}



117

Straight-line drawings of a triangulation G with n vertices in R^{2n} problems



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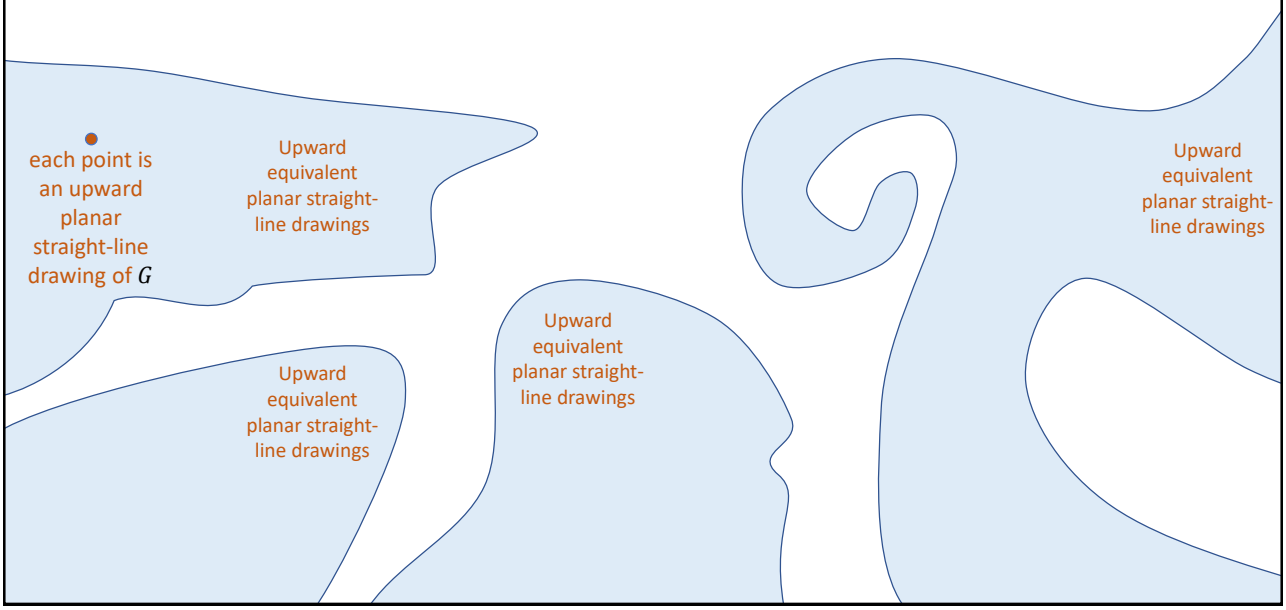
morphs
upward planar straight-line drawings of upward-planar graphs

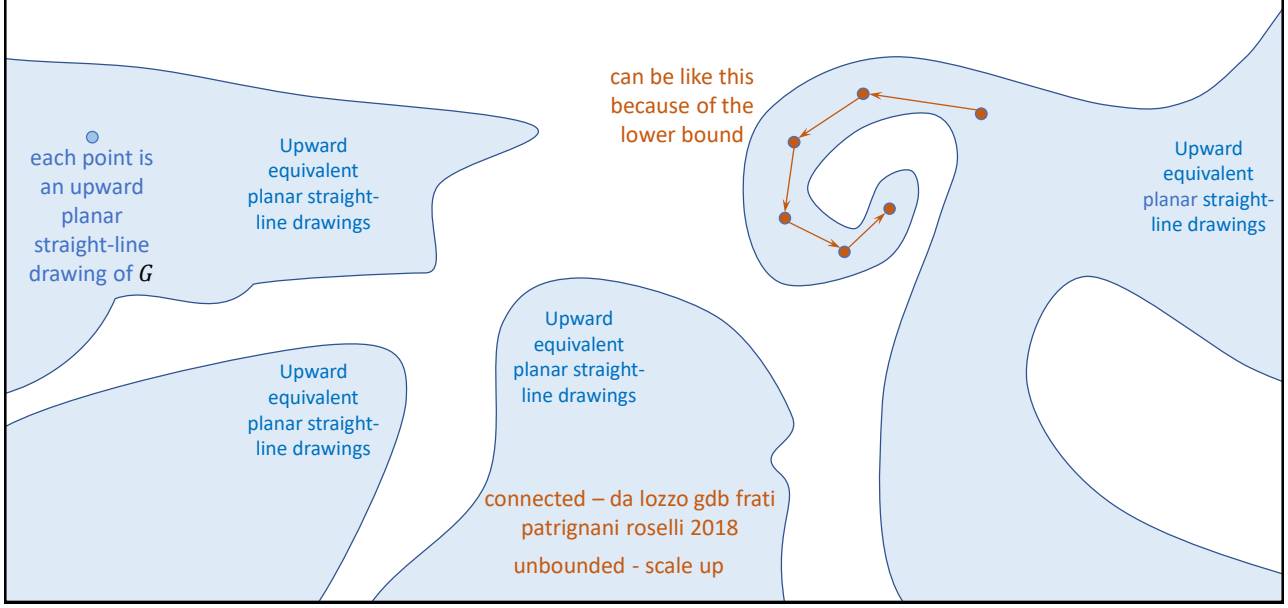
119

Upward straight-line drawings of an upward planar graph G with n vertices in R^{2n}



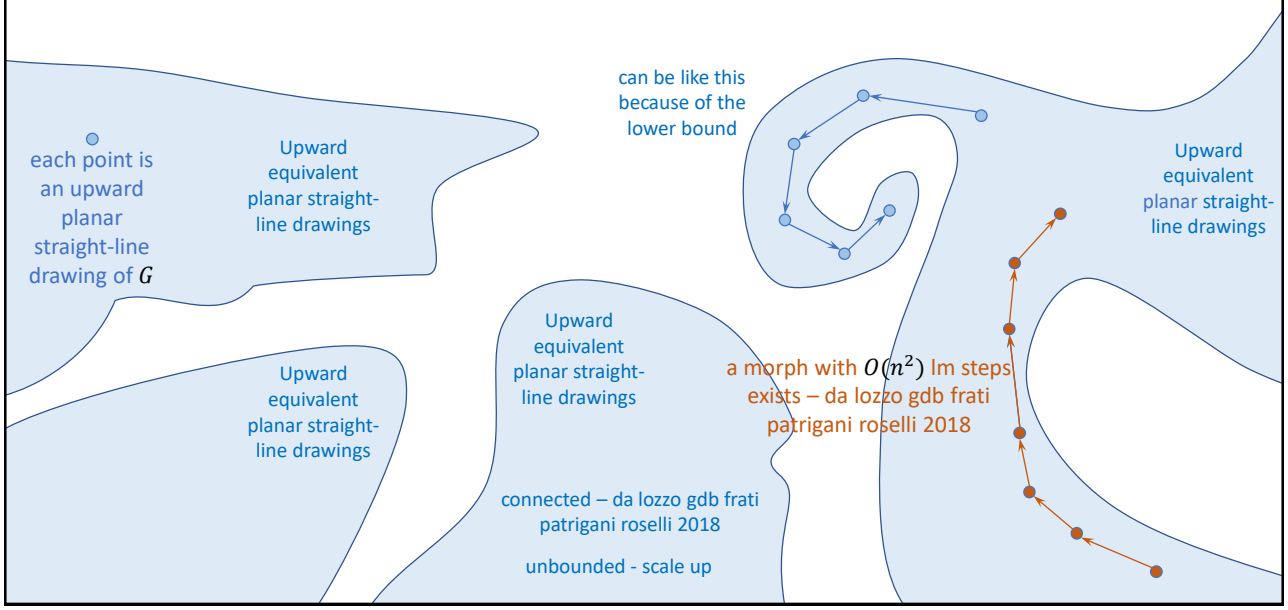
120

Upward straight-line drawings of an upward planar graph G with n vertices in R^{2n}



121

Upward straight-line drawings of an upward planar graph G with n vertices in R^{2n}



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morphs
upward planar straight-line drawings of rooted trees

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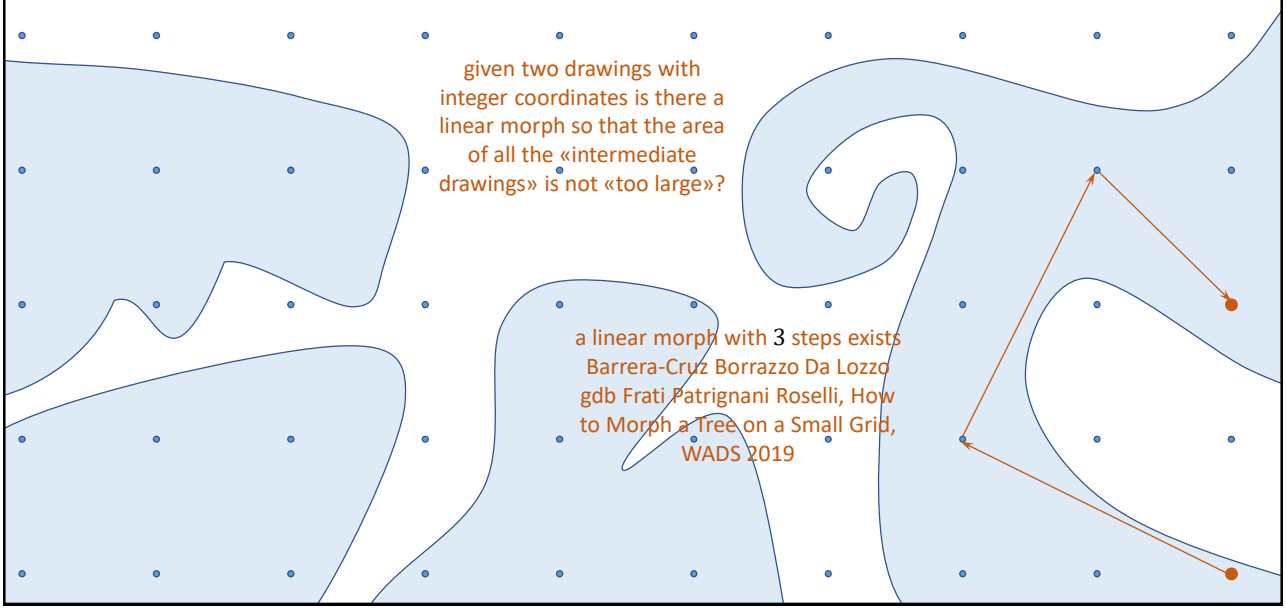
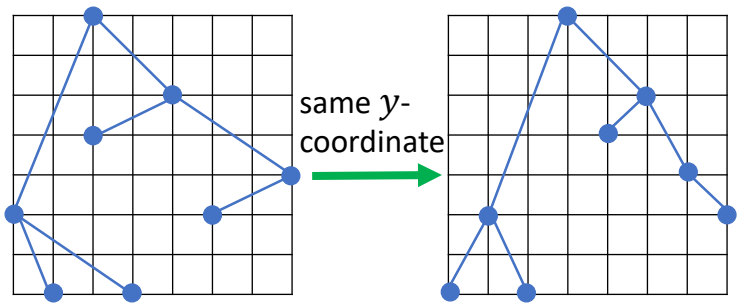
Upward straight-line drawings of a rooted binary tree T with n vertices in R^{2n}



124

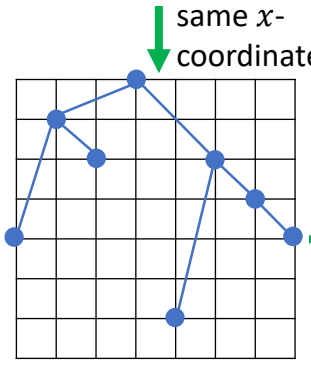


Γ_0

This Slide: Courtesy of Fabrizio Frati

Uses ideas from:

Da Lozzo gdb Frati, Patrignani Roselli, Upward Planar Morphs, GD 2018



Γ_1

Employs proof techniques of:

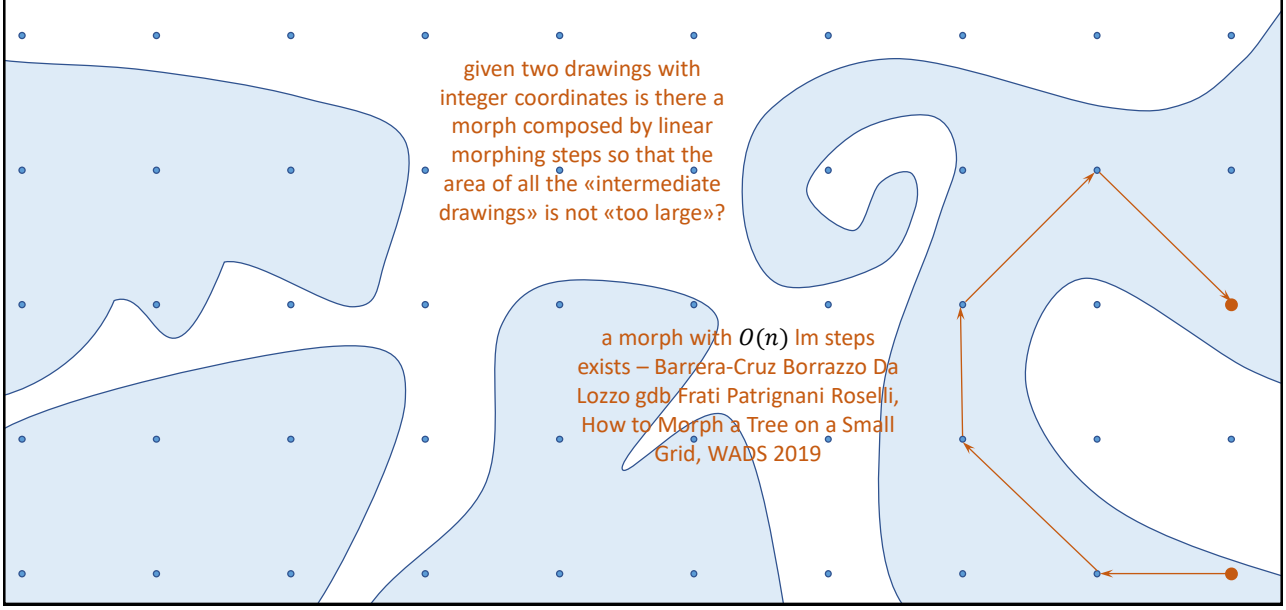
Alamdari Angelini Barrera-Cruz Chan Da Lozzo gdb Frati Haxell Lubiw Patrignani Roselli Singla Wilkinson. How to Morph Planar Graph Drawings, SICOMP 2017

125

Upward straight-line drawings of a rooted tree T with n vertices in R^{2n}

given two drawings with integer coordinates is there a morph composed by linear morphing steps so that the area of all the «intermediate drawings» is not «too large»?

a morph with $O(n)$ lm steps exists – Barrera-Cruz Borrazzo Da Lozzo gdb Frati Patrignani Roselli, How to Morph a Tree on a Small Grid, WADS 2019



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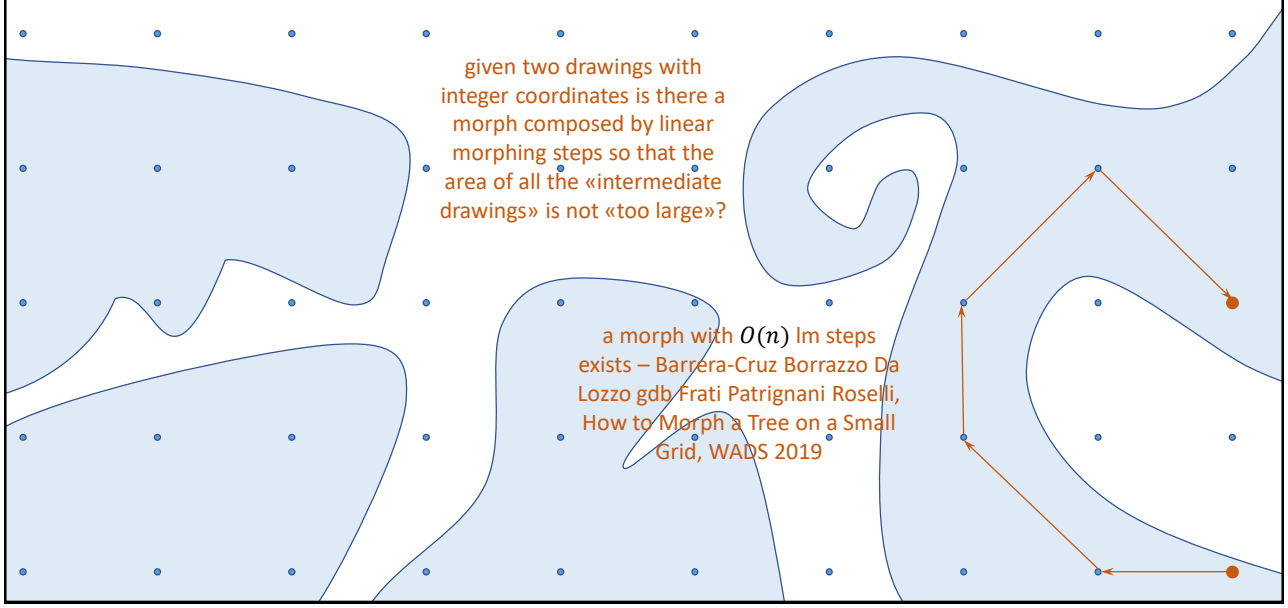
Straight-line drawings of a tree T with n vertices in R^{2n}

given two drawings with integer coordinates is there a morph composed by linear morphing steps so that the area of all the «intermediate drawings» is not «too large»?

a morph with $O(n)$ lm steps exists – Barrera-Cruz Borrazzo Da Lozzo gdb Frati Patrignani Roselli, How to Morph a Tree on a Small Grid, WADS 2019



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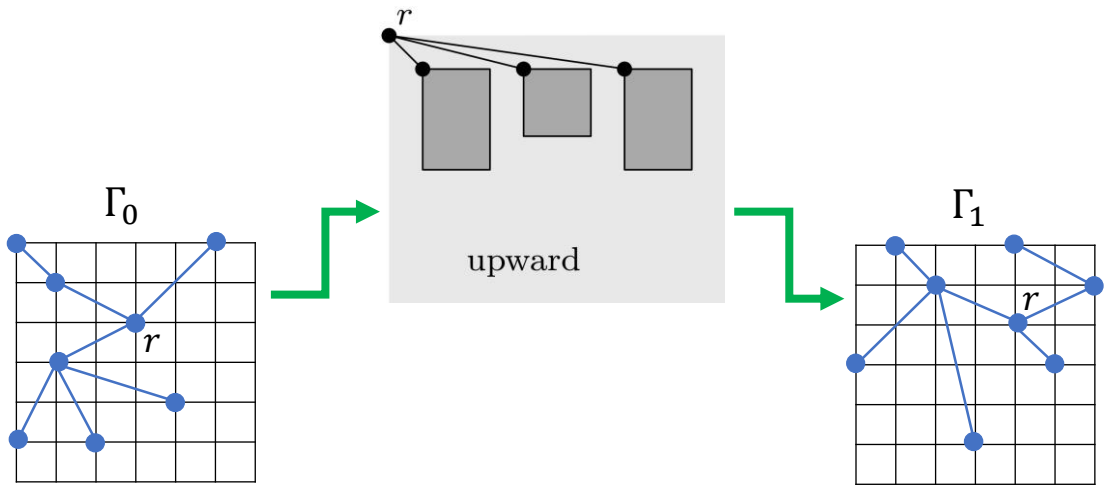
General strategy

This Slide: Courtesy of Fabrizio Frati



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More GD topics that deal with time

- Simultaneous embedding with fixed edges (SEFE)
  - Time is in layers
- Phylogenetic Networks
  - Represent the evolution over time
- Greedy drawings
  - Time is in routing
- Constraints
  - Objects that do not change in the graph do not change in the drawing
- Drawing extensions
  - The graph grows during time

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More generally ….

- All Graph Drawing Papers consider time
- Some of them focus only on instant $t = 0$

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This Is Time for Graph Drawing

Giuseppe Di Battista
Università degli Studi Roma Tre

27th International Symposium on Graph Drawing and Network Visualization – GD2019
Průhonice/Prague, September 17-20, 2019

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