Druid

Representation of Interwoven Surfaces in 2½D Drawing

Keith Wiley

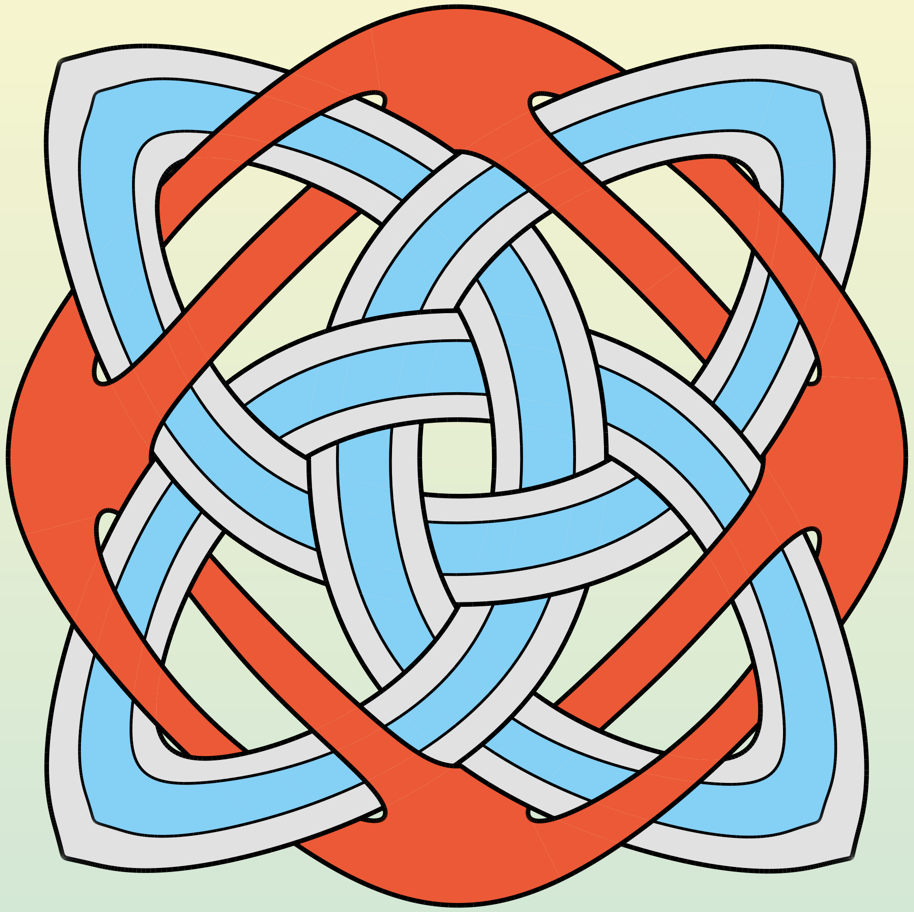
Thesis advisor: Lance R. Williams

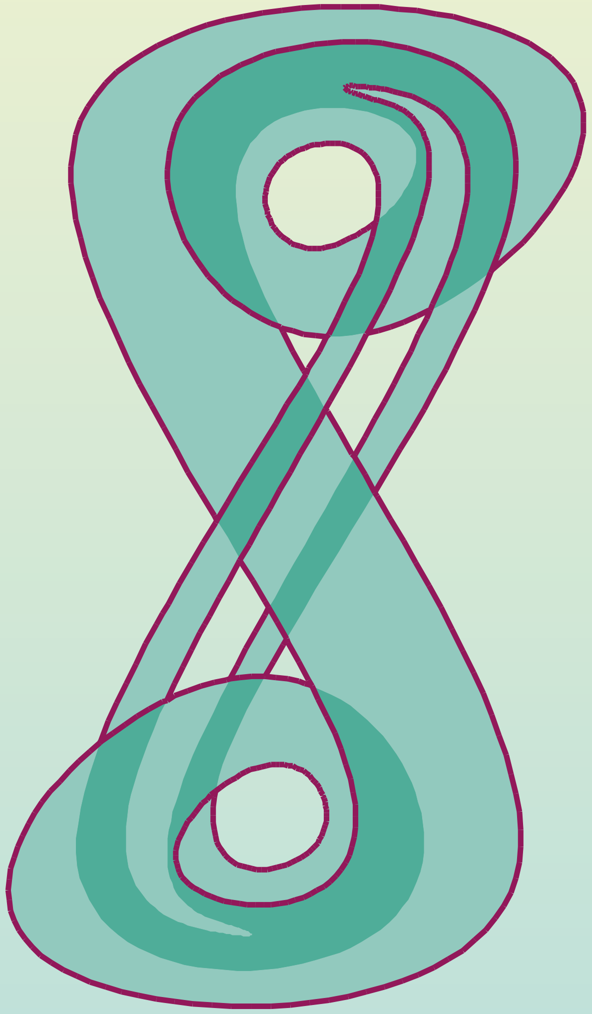
University of New Mexico

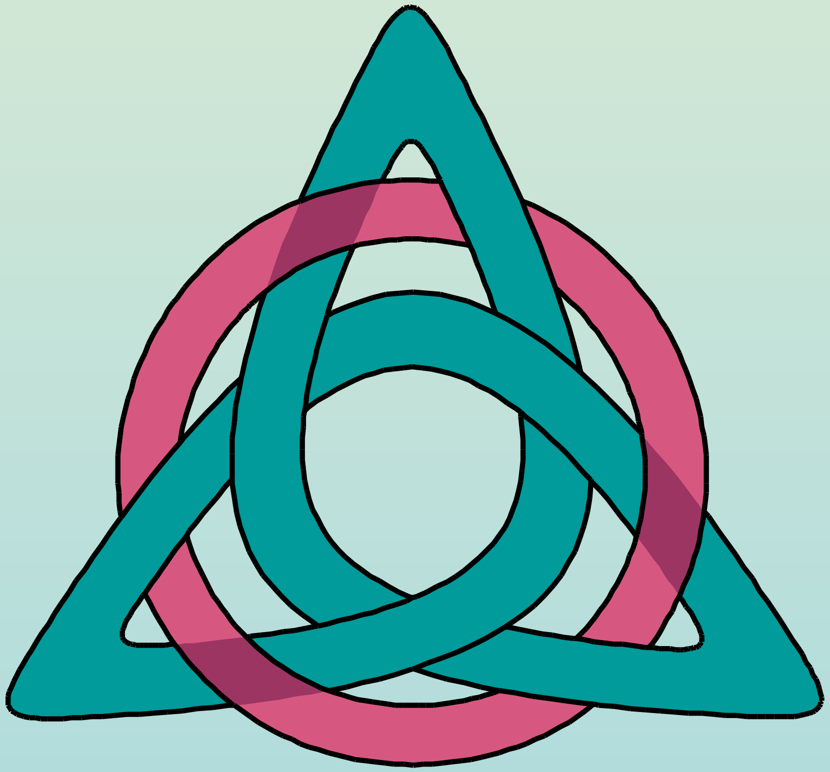
Department of Computer Science

Albuquerque, NM 87131 USA

Interwoven 2½D Scenes



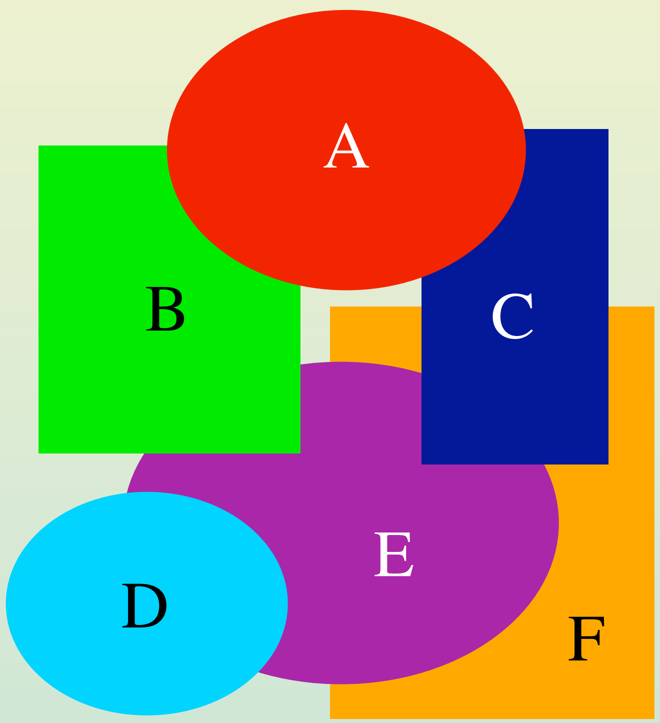


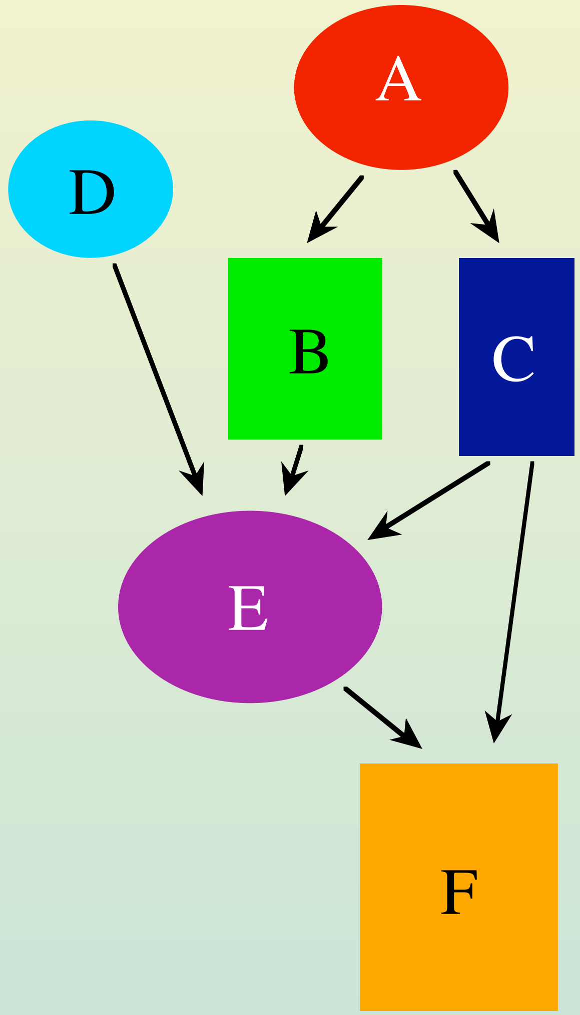


Introduction

Existing drawing programs:

- Use distinct layers
- Impose a DAG
- Do not permit interwoven surfaces





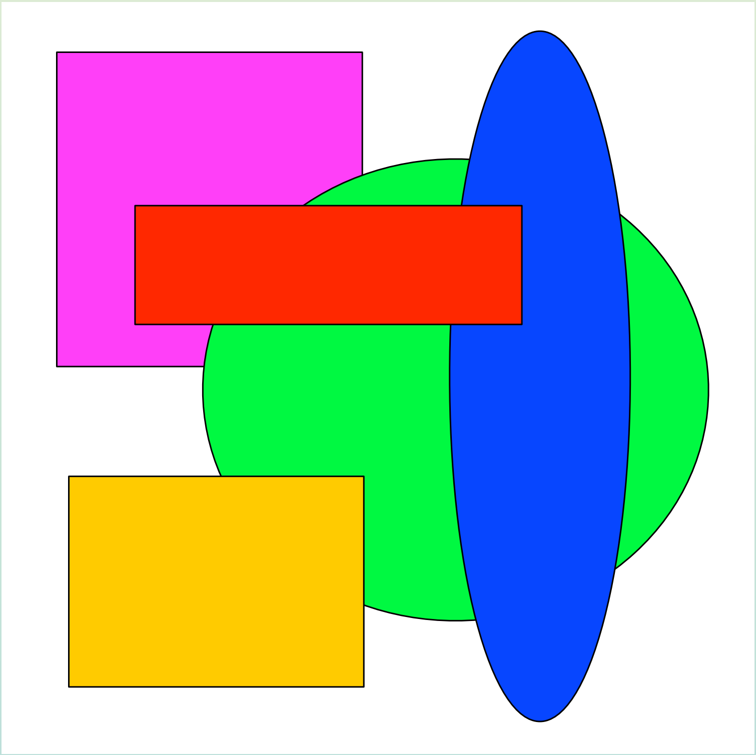
Our program, ***Druid***, does not suffer from these limitations.

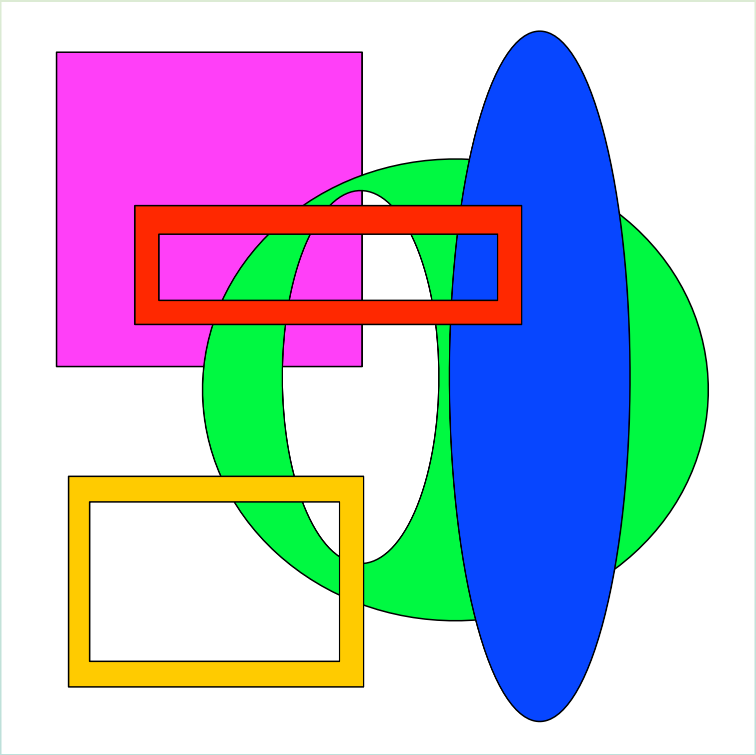
Existing Drawing Programs

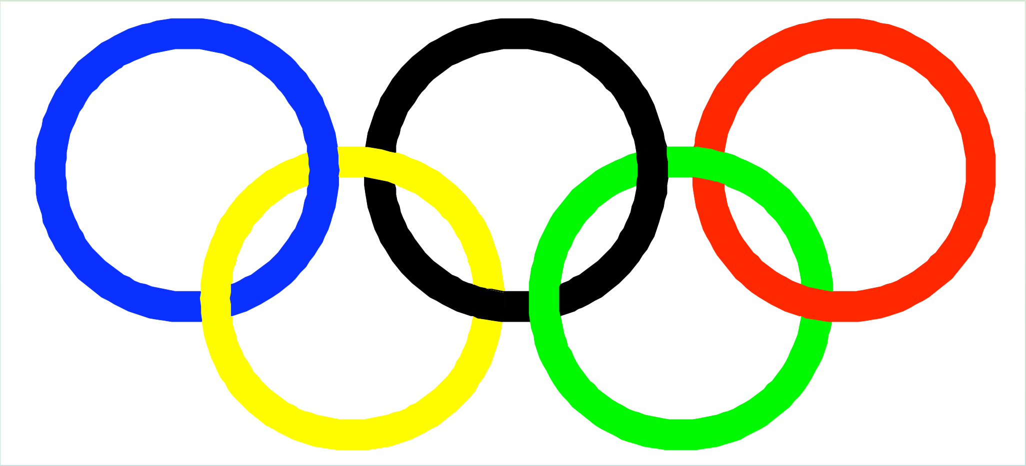
Noninterwoven layers

Boolean combinations of boundaries, *i.e.*, holes.

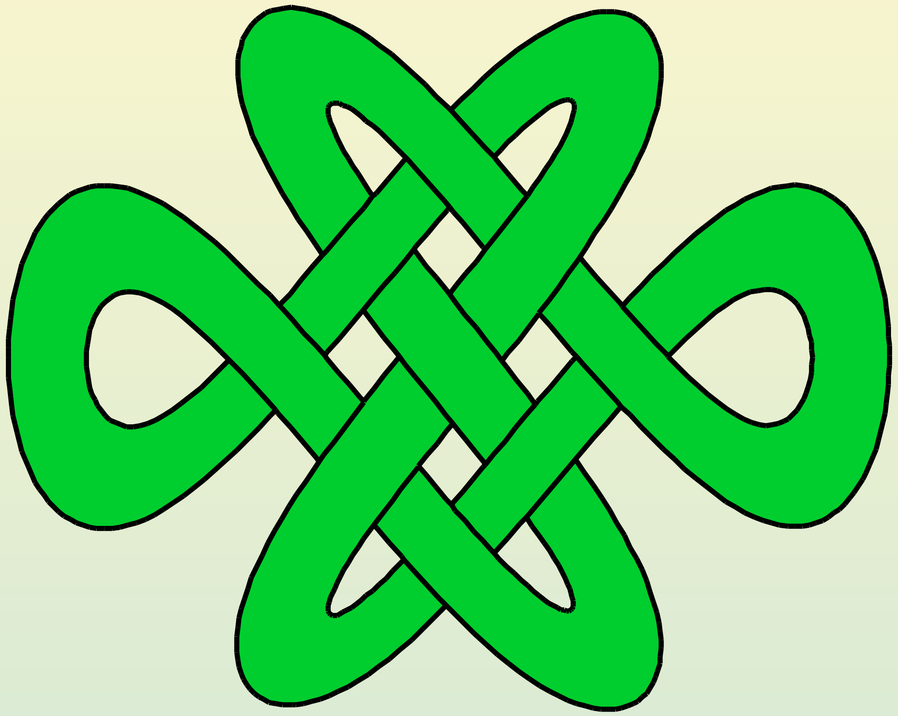
Do not span the full space of ***2½D scenes***.

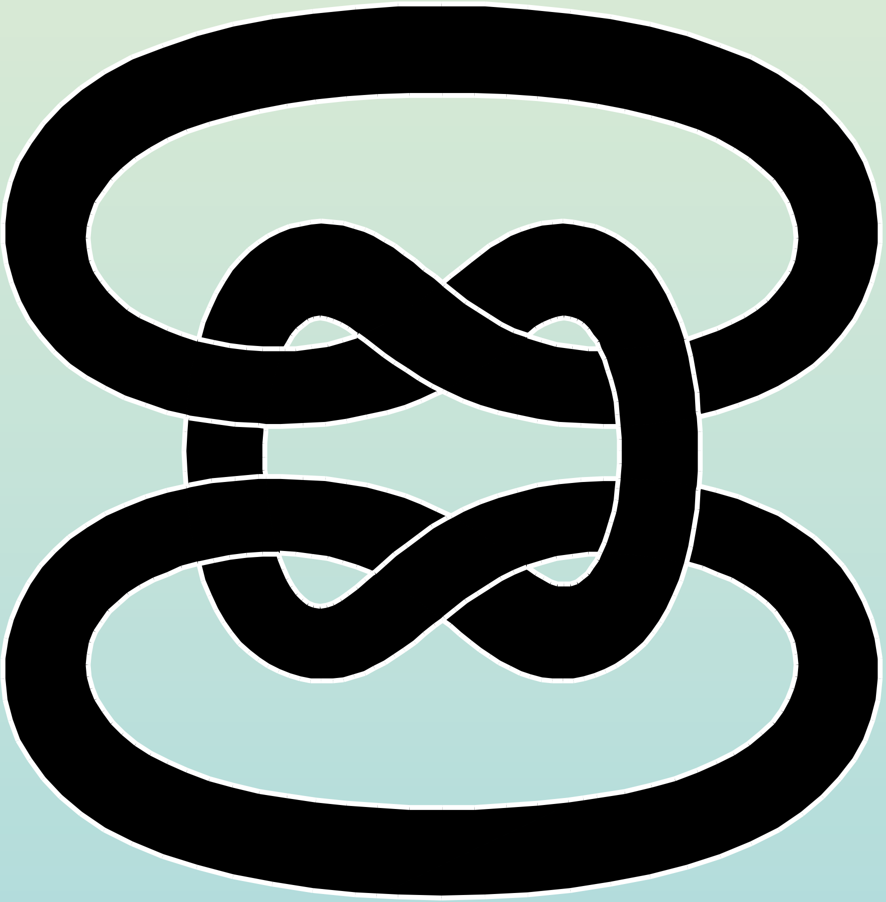


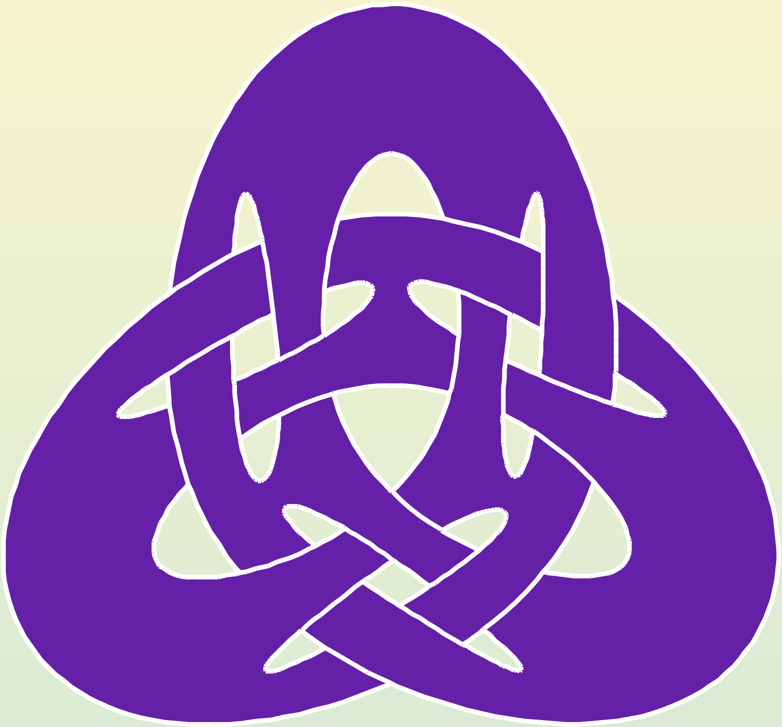




Knots vs. Interwoven Surfaces







Interwoven Surfaces in Conventional Drawing Programs

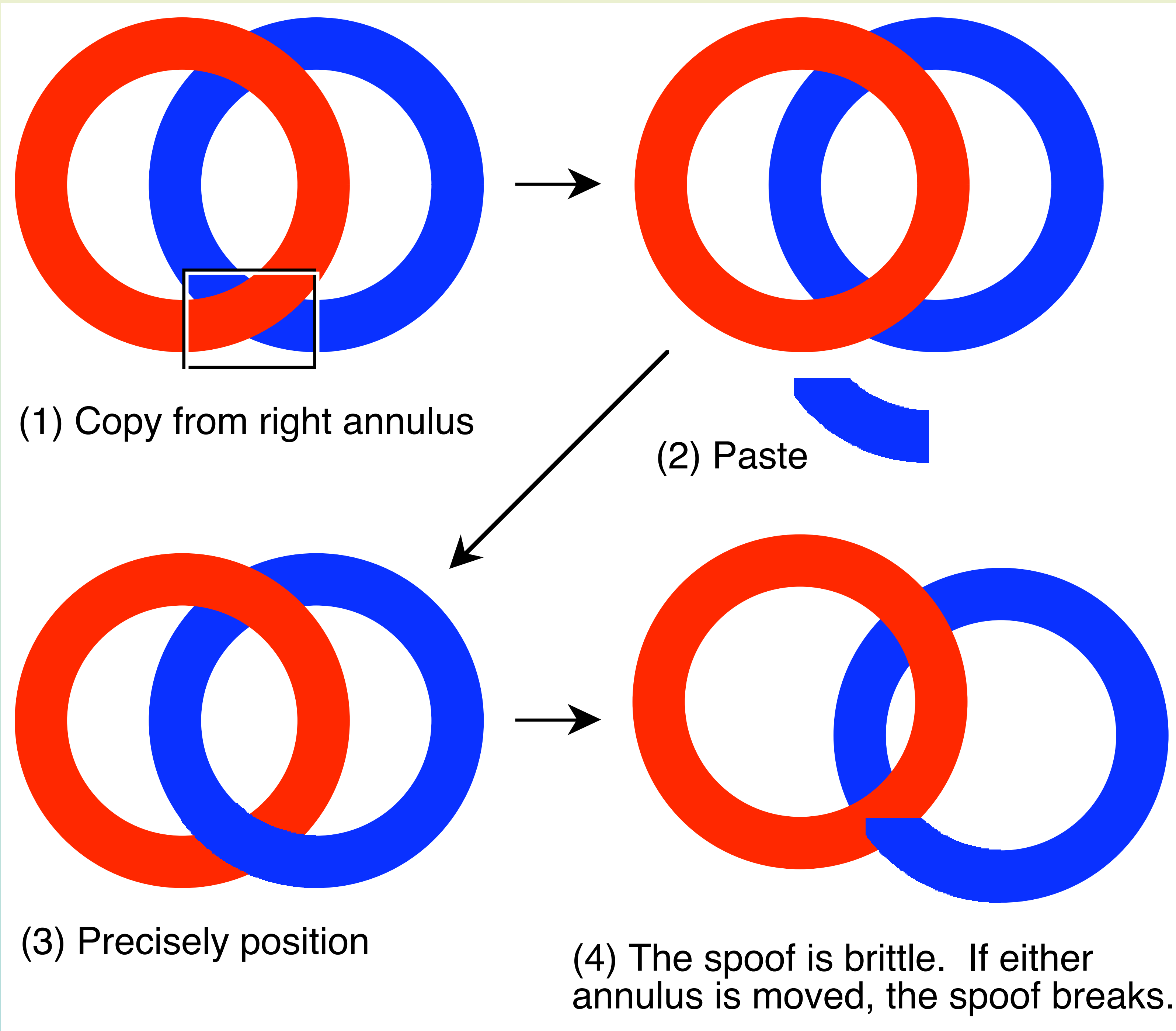
1. Spoofs

2. Painting planarized graphs,
   e.g., *Adobe Illustrator*

3. Local DAG manipulation,
   e.g., *MediaChance Real-Draw*

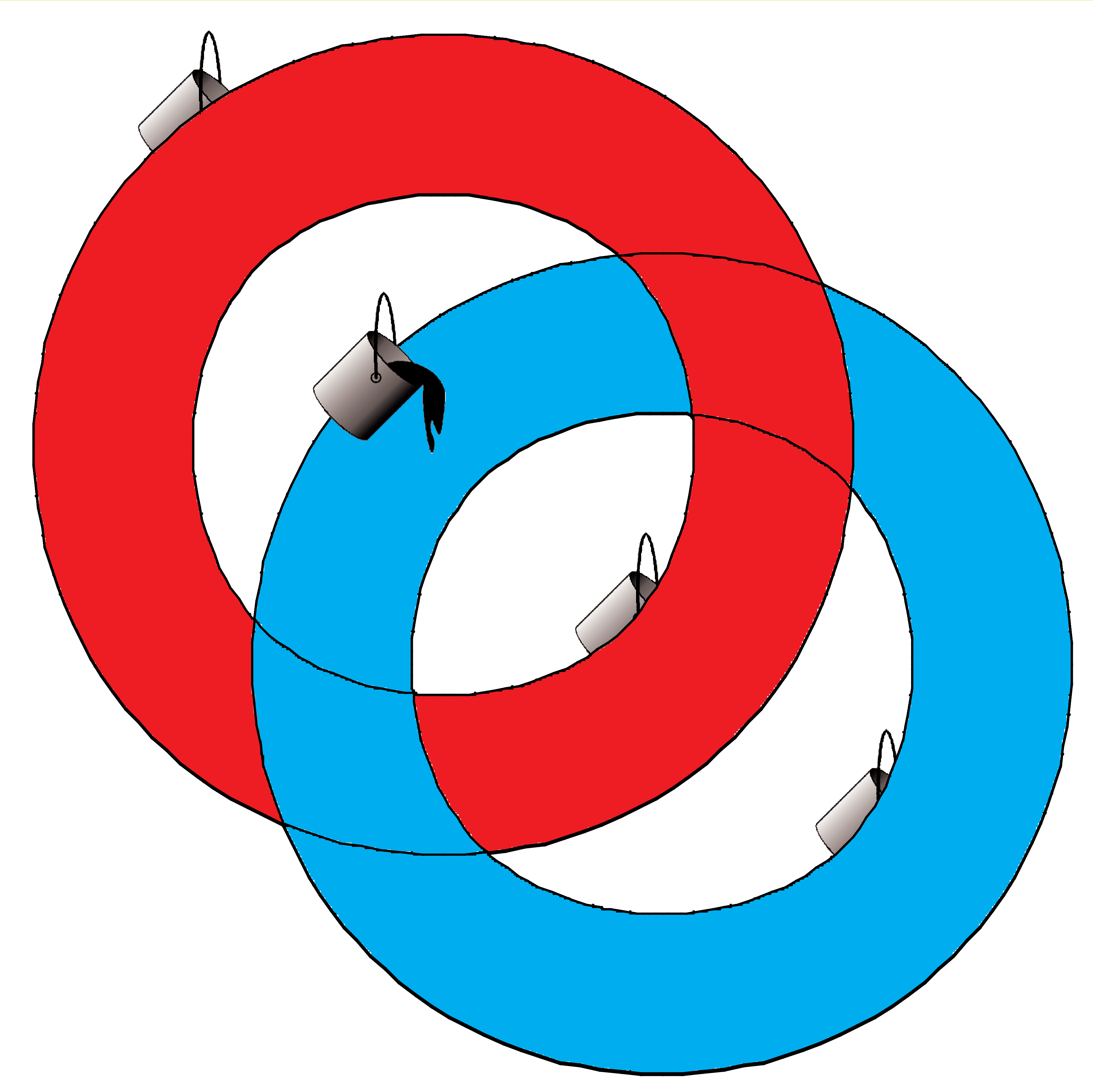
Spoofs

A layered arrangement that produces the illusion of interwoven surfaces



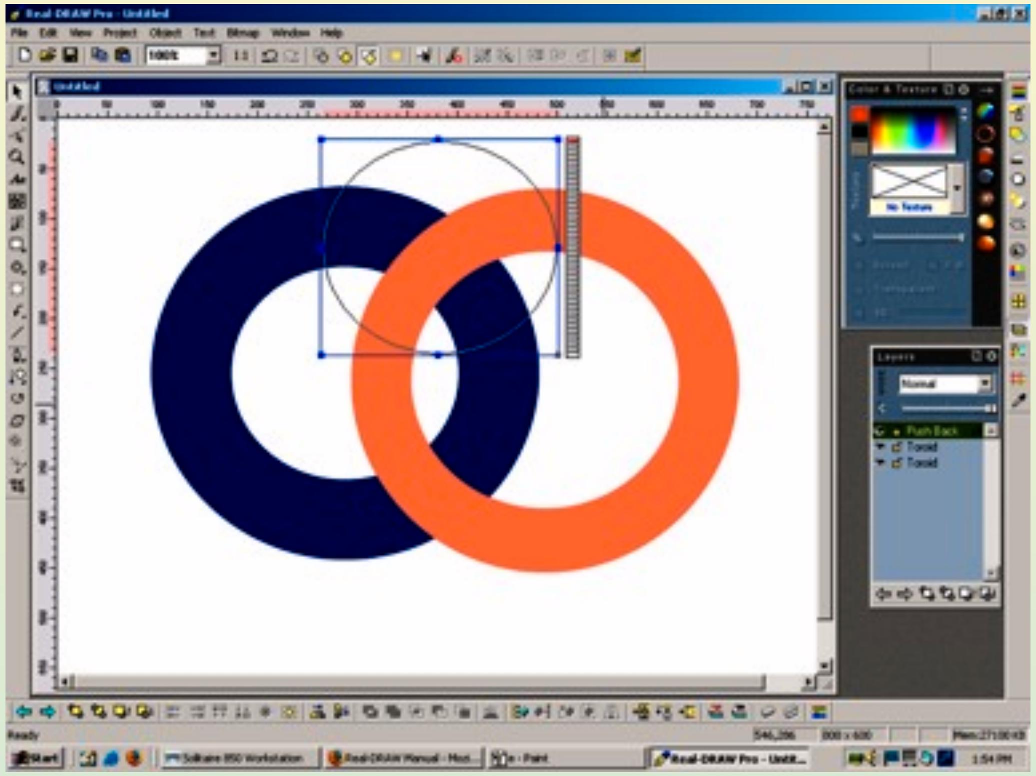
- Tedious to construct
- Tedious to maintain

Adobe Illustrator Method



- Convert drawing to planar graph
- Paint faces of the graph independently

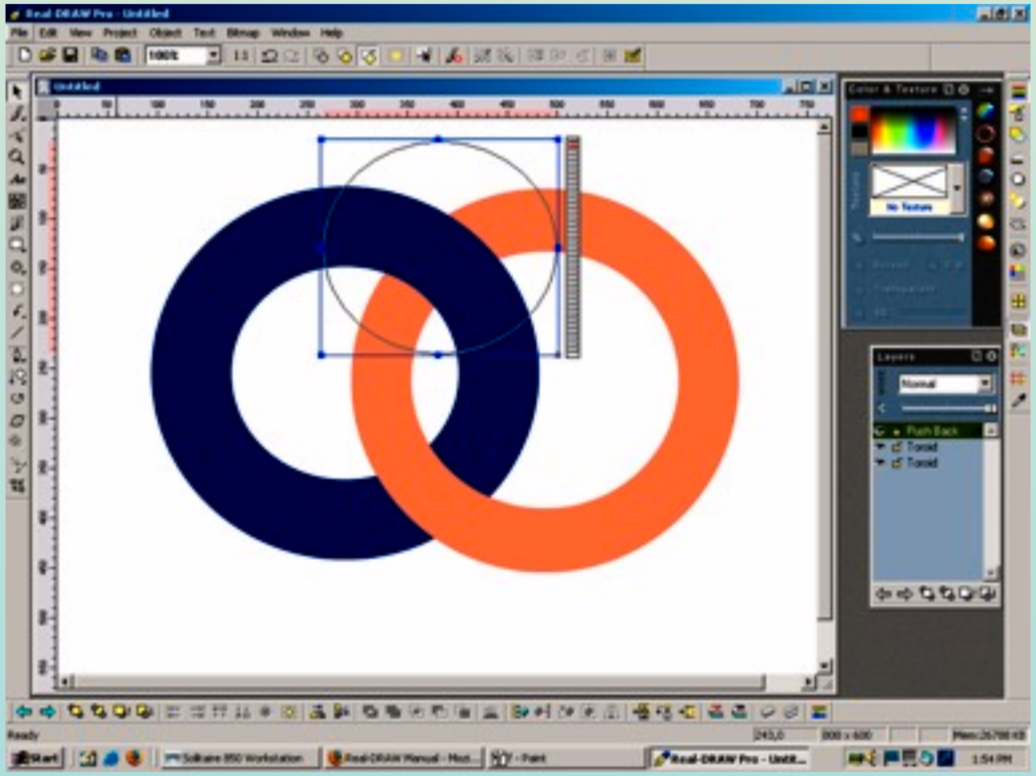
MediaChance Real-Draw Pro-3

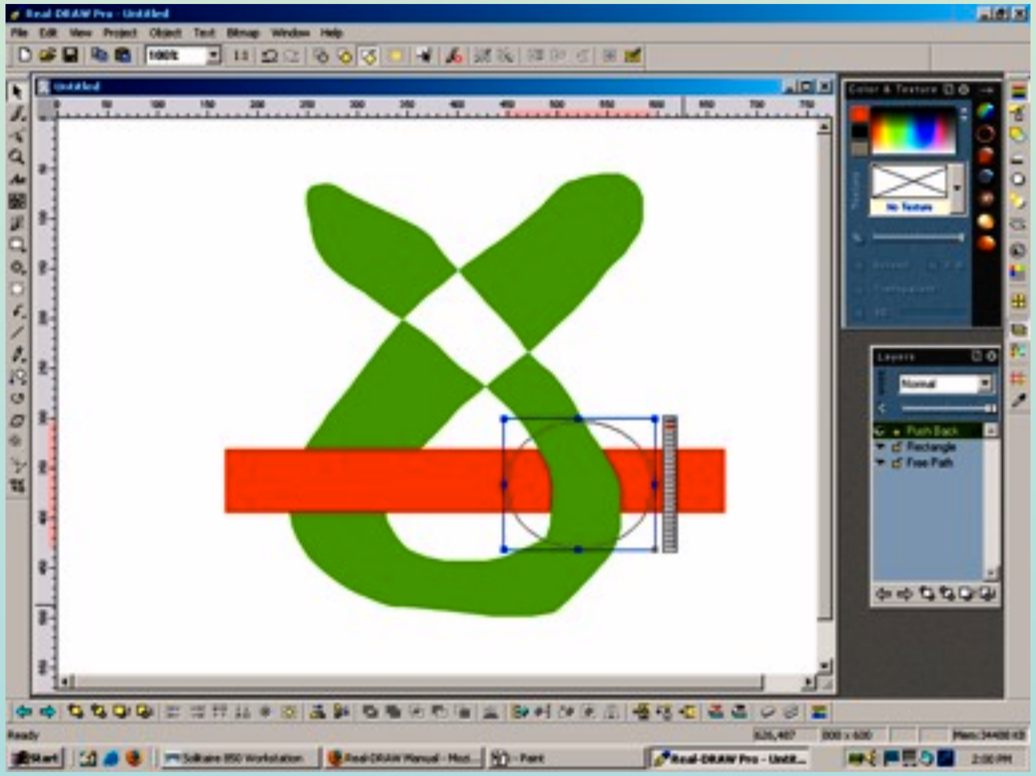


Push-back tool: The user can push the top layer down (figures left)

- Insufficient for transparent surfaces
- Cannot represent self-overlapping surfaces (figure below)

The right annulus is pushed down





Affordances

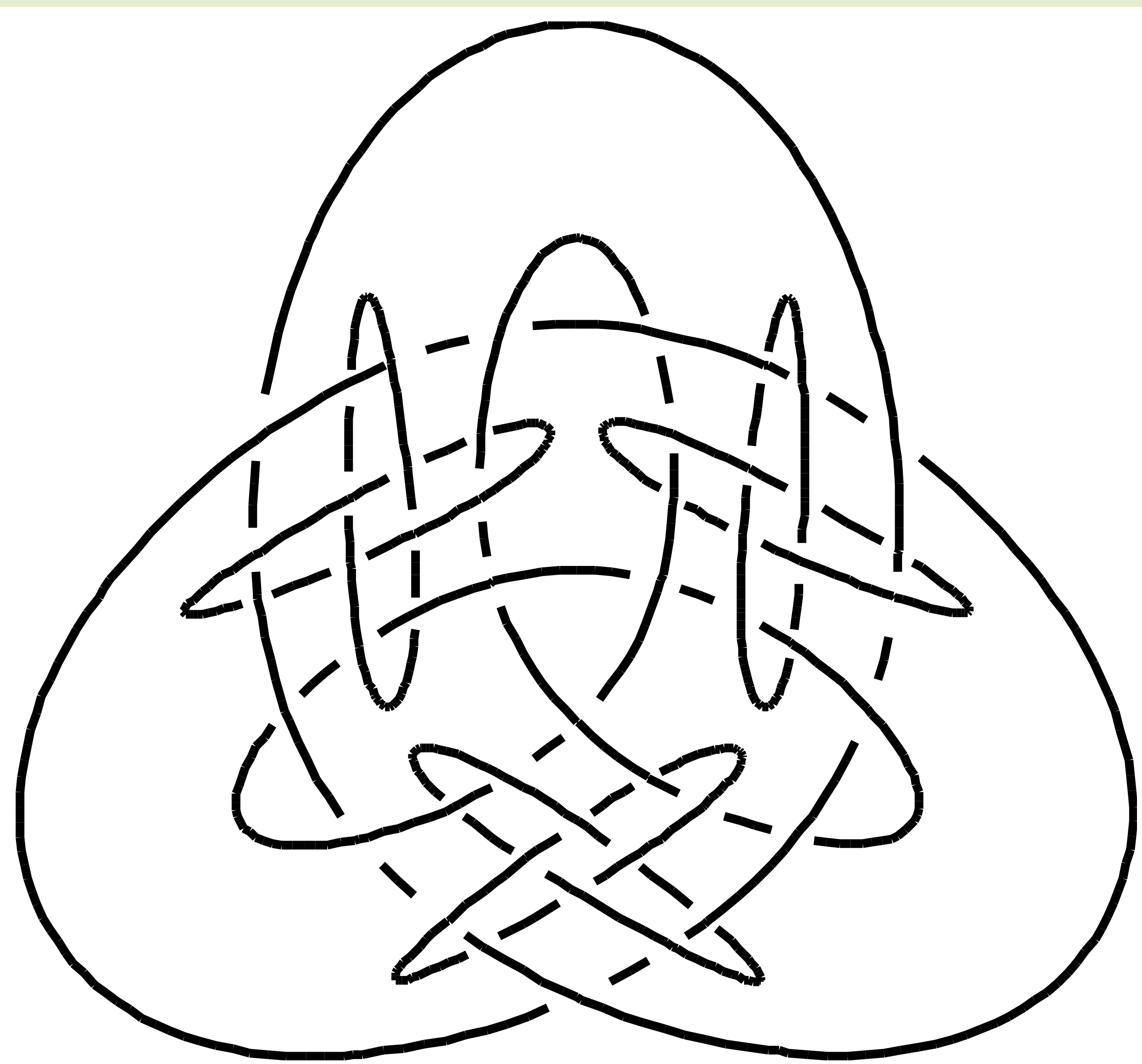
- ***Feasability*** is not the sole issue. ***Convenience*** and ***naturalness*** are also issues.
- ***Affordances***: The set of interactions that a physical object suggests for itself (Norman '02).
- Unlike conventional drawing programs, *Druid's* affordances are isomorphic to those of idealized physical surfaces.
- The user's experience is of interacting with surfaces, not pictures of surfaces.

Norman, D. A., *The Design of Everyday Things*, Basic Books, 2002.

Druid's Representation

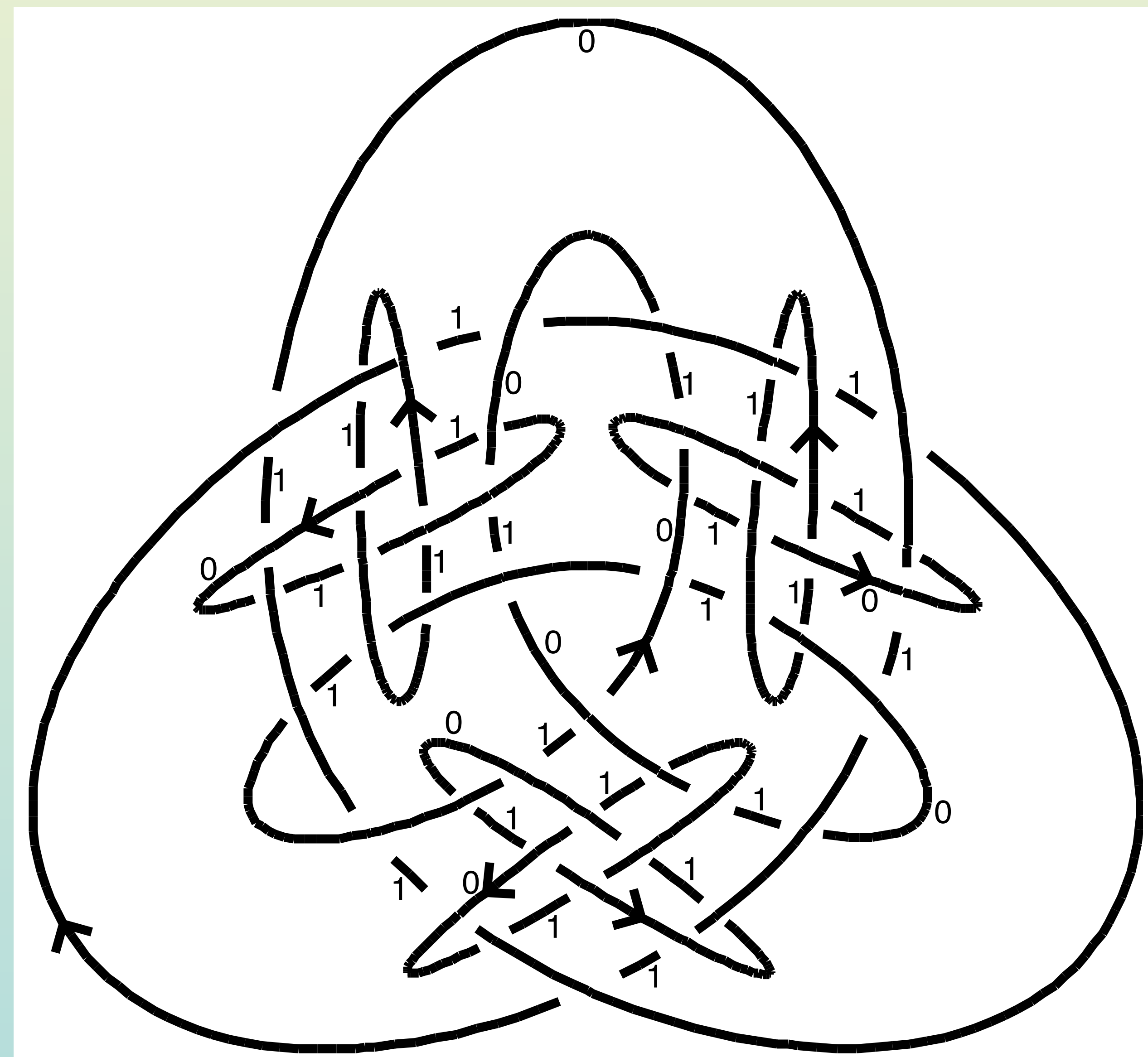
Knot-diagram:

A projection of closed curves indicating which curve is above where two cross



Labeled knot-diagram (Williams '94):

Sign of occlusion for every boundary (arrows)
Depth index for every boundary segment

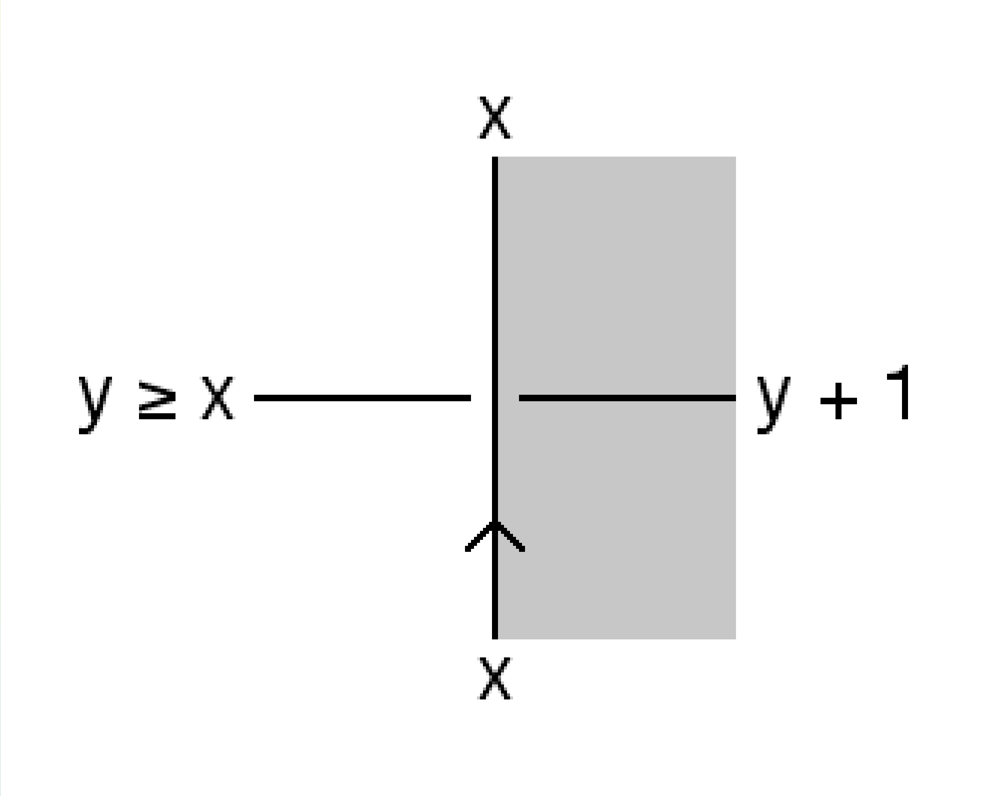


Williams, L. R., *Perceptual Completion of Occluded Surfaces*, PhD dissertation, Univ. of Massachusetts at Amherst, Amherst, MA, 1994.

Labeling Scheme

Imposes local constraints on the four boundary segment depths at a crossing

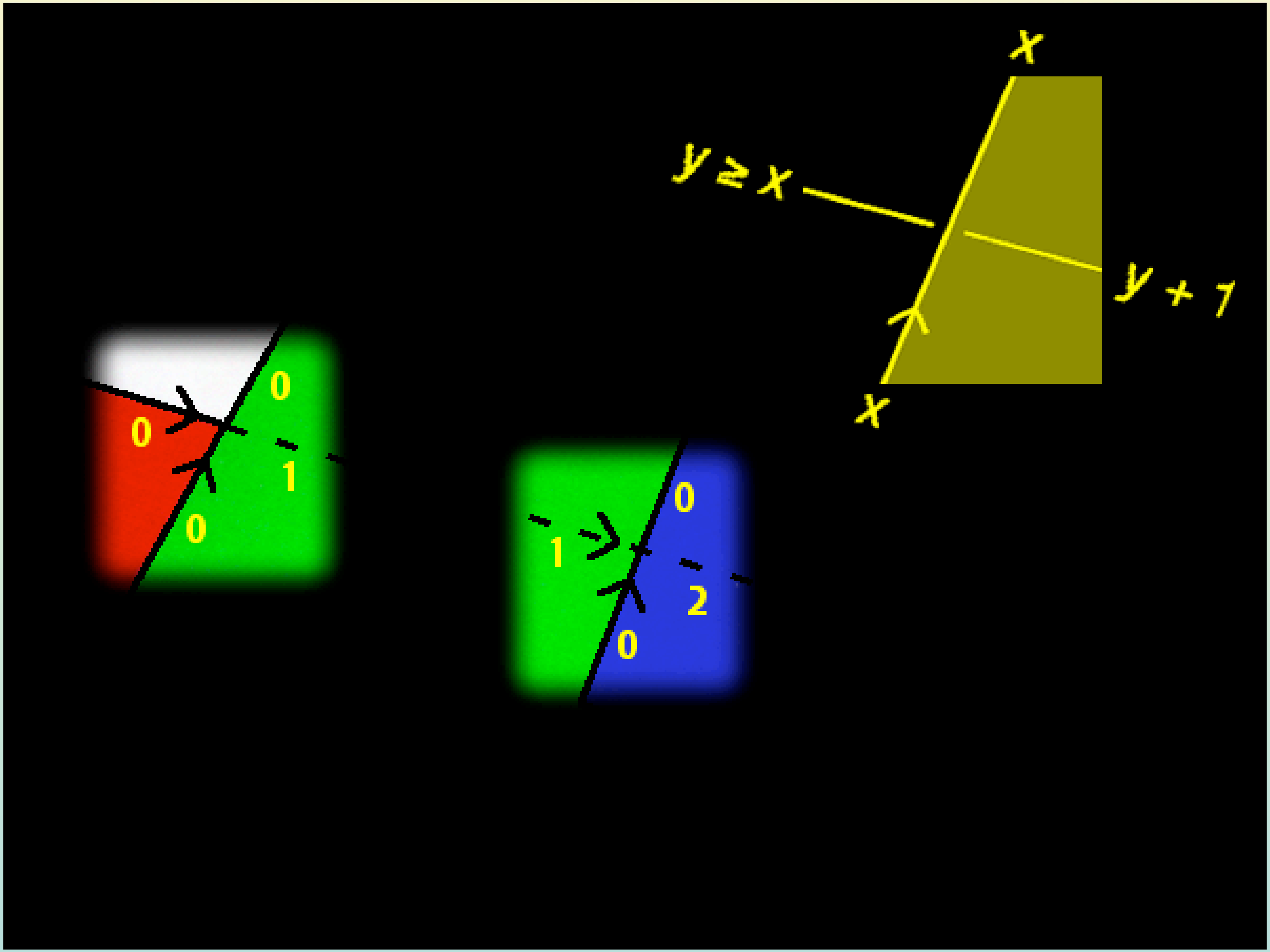
x, *y*: boundary segment depths



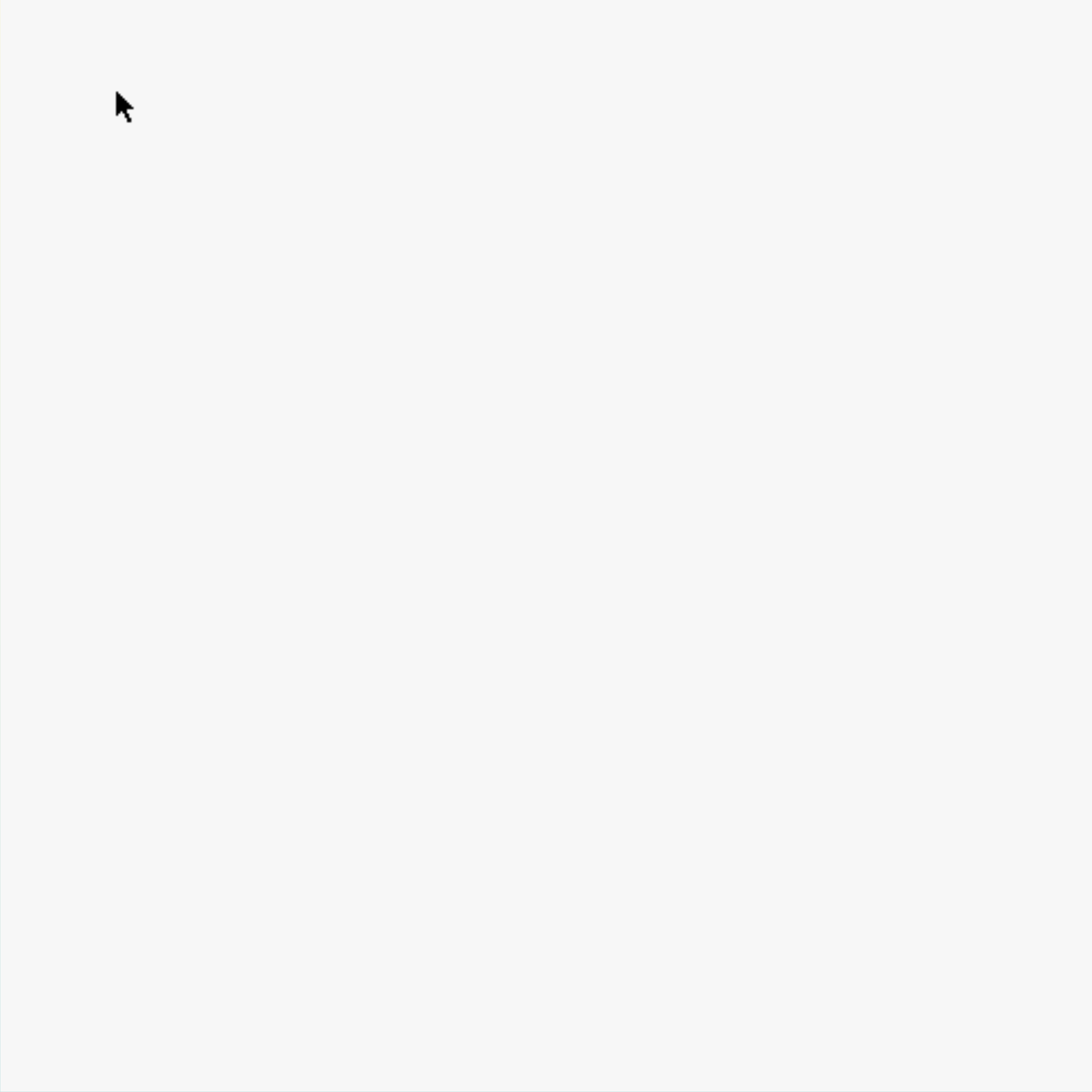
Legal labeling: A labeling in which every crossing satisfies the ***labeling scheme*** (Williams '94)

Williams, L. R., *Perceptual Completion of Occluded Surfaces*, PhD dissertation, Univ. of Massachusetts at Amherst, Amherst, MA, 1994.

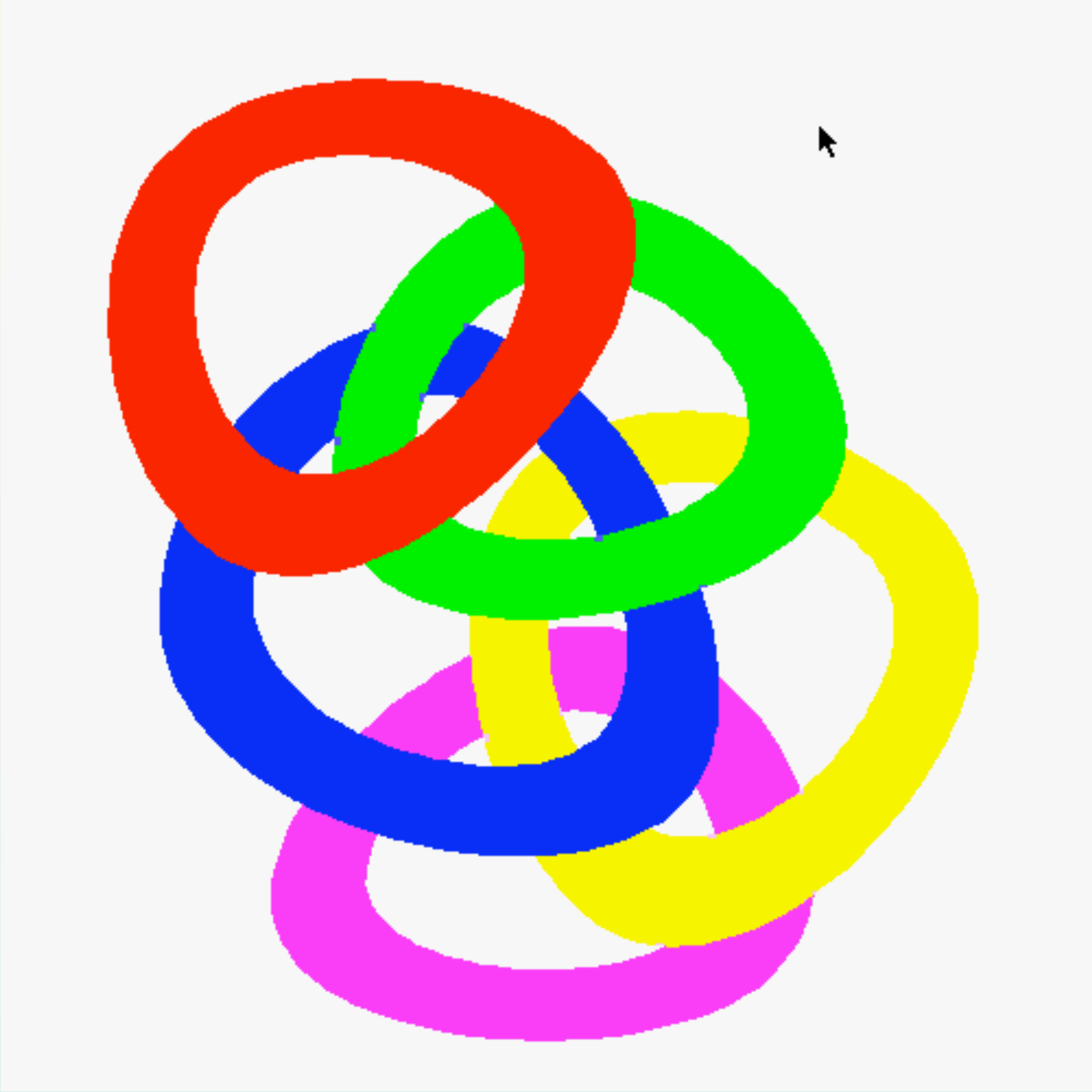
Labeling Scheme Justification



Using *Druid*



The *Crossing-Flip* Interaction



Drawing Program Interactions

- Create & delete boundaries
- Reshape & drag boundaries
- Crossing flip (Invert two surfaces' relative depths in an area of overlap)
- Sign-of-occlusion flip

Effects of Interactions on the Labeling

Requiring relabeling (topological change)

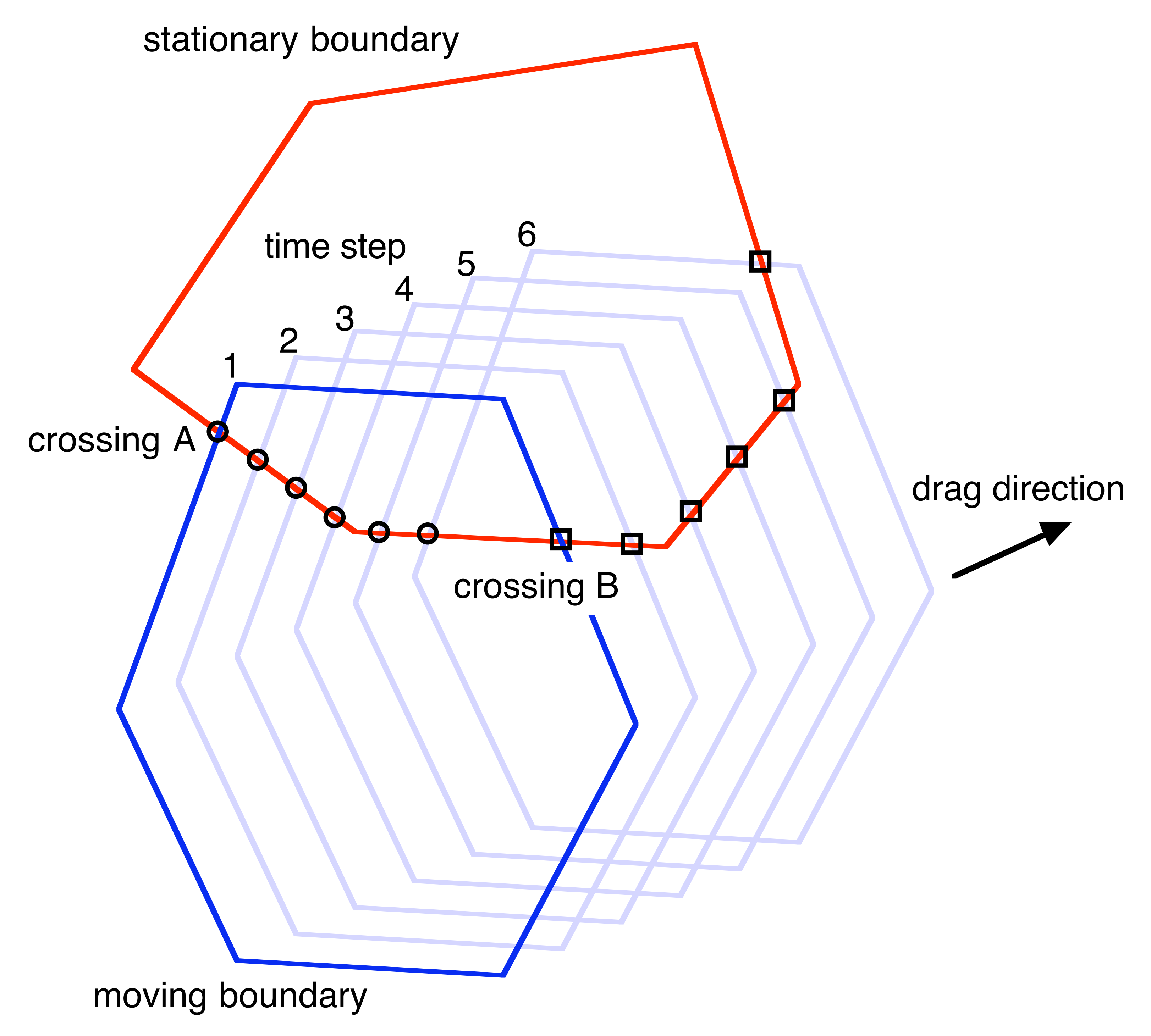
- Creation & deletion of crossings
- Reordering of crossings around boundaries
- Crossing-state flips
- Sign-of-occlusion flips

Not requiring relabeling (no topological change)

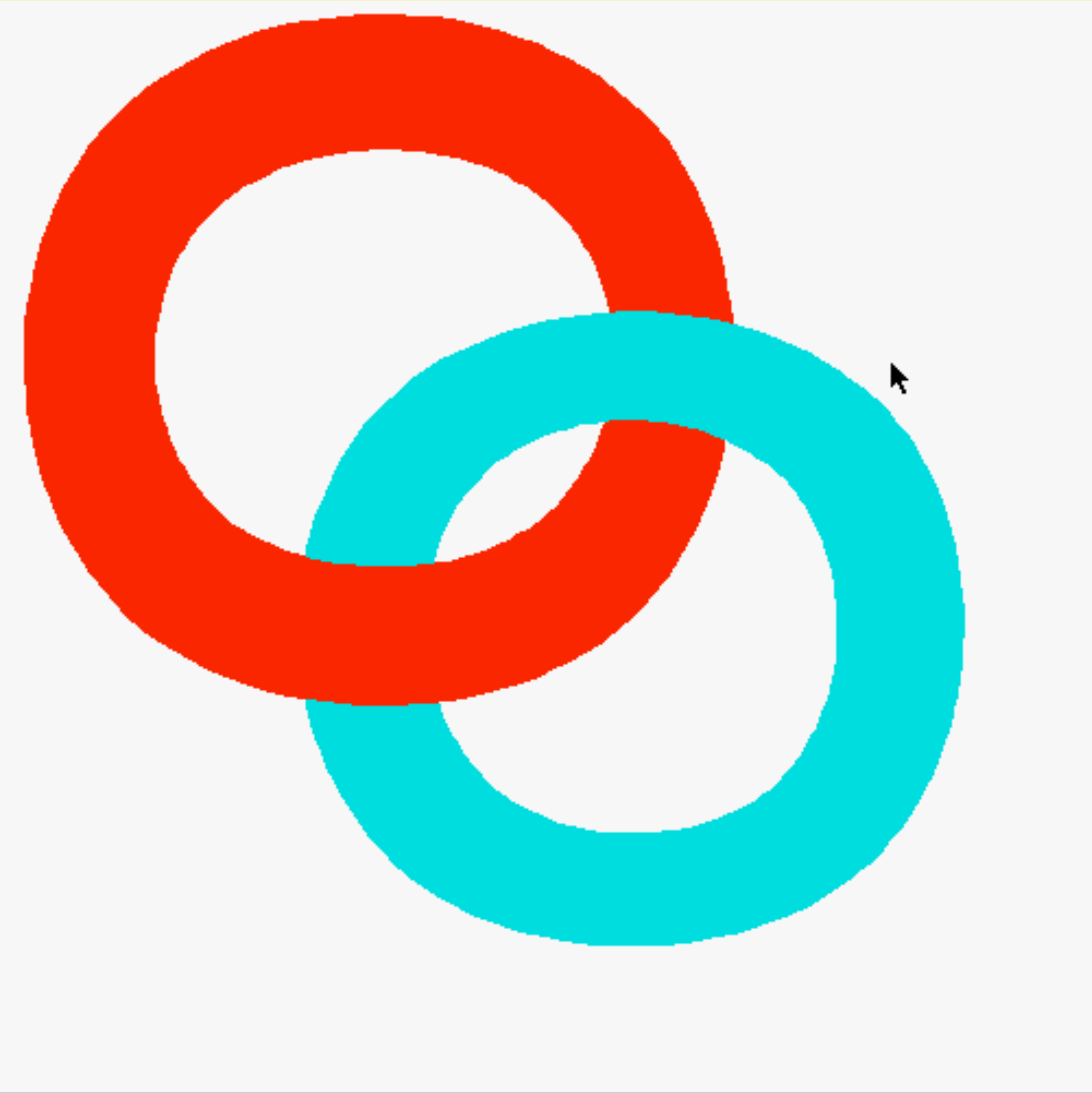
- Reshaping or dragging boundaries without causing topological changes

Crossing Projection

- Important to preserve crossing-states
- Naive destruction/ rediscovery of crossings would lose crossing-states
- *Druid* **projects crossings as they move around boundaries**



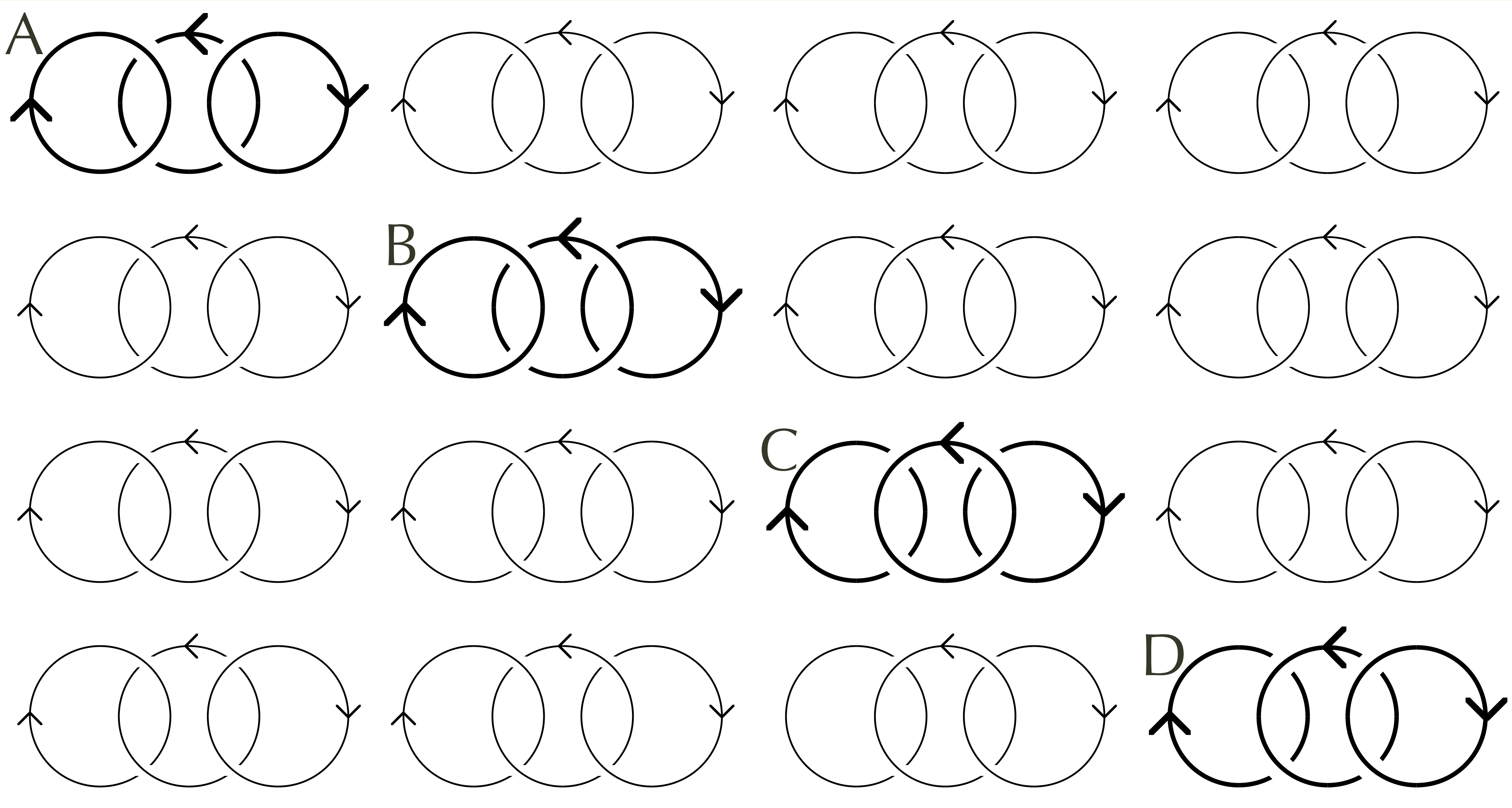
Demonstration of *Druid*

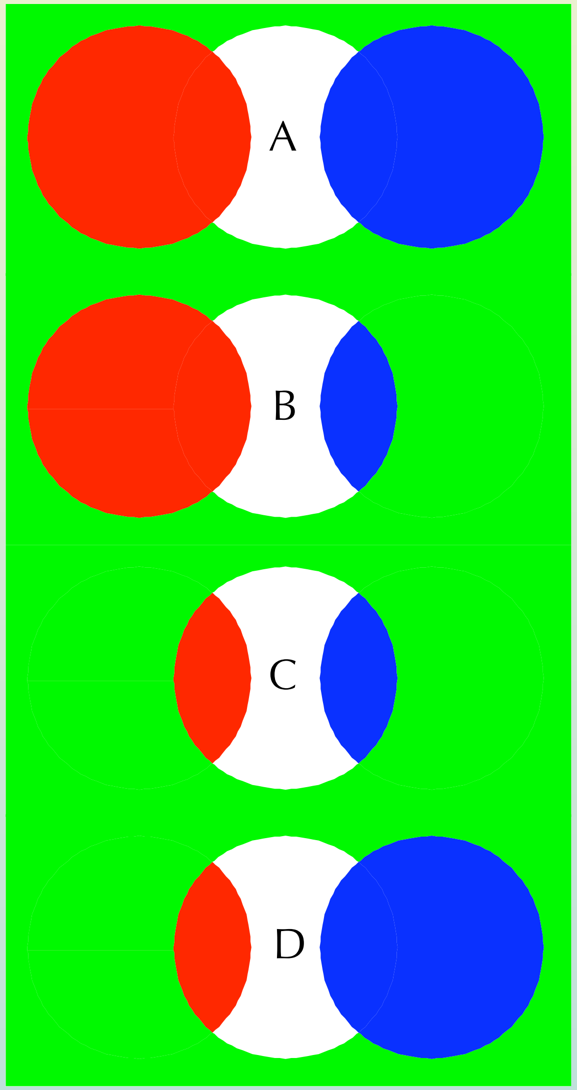


- *Druid* knows to move both boundaries at once.
- *Druid* relabels when the interlock breaks.

Finding a Legal Labeling

Labeling space: Possible labelings for a labeled knot-diagram. Labeling space size: 2^c

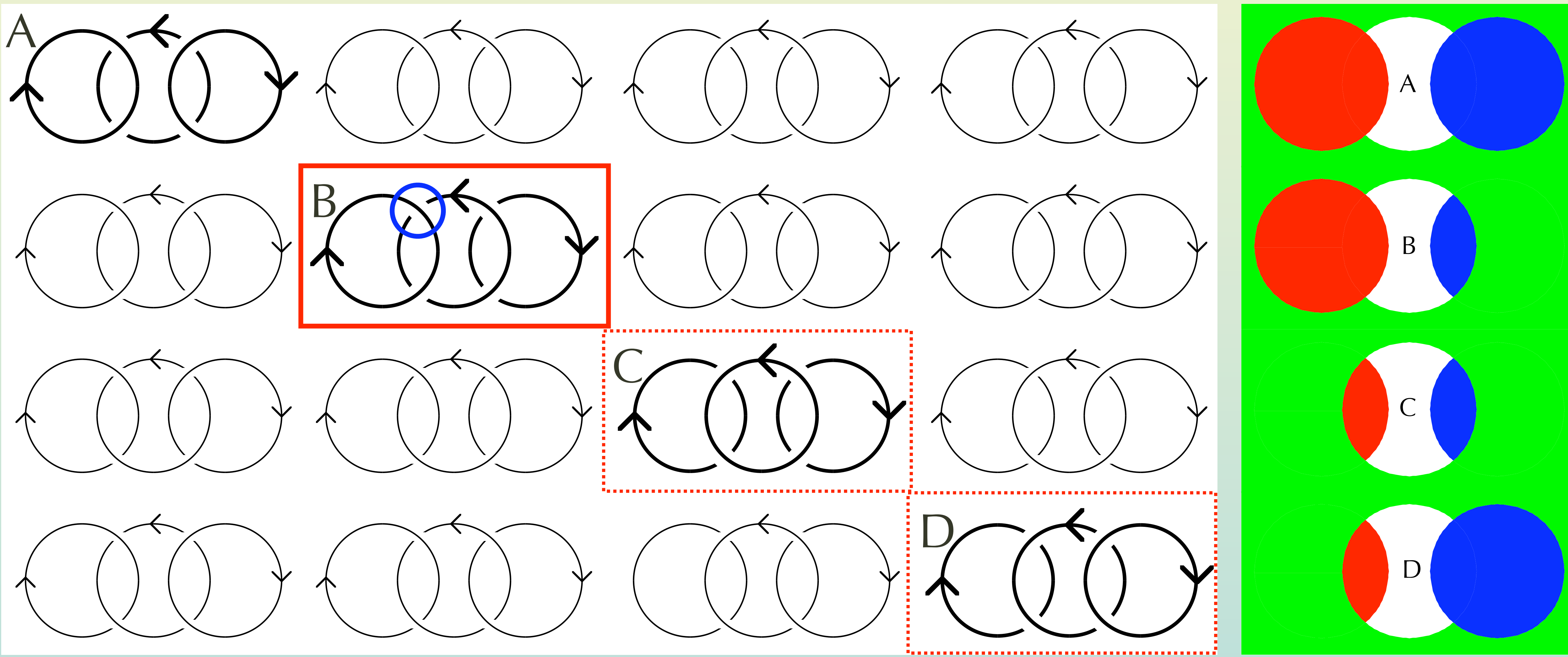




Druid maintains a legal labeling automatically.

Minimum-Difference Search

Druid searches the *labeling space* for the ***minimum-difference labeling***.



- Labeling is currently in state *B*.
- User clicks the blue-circle marked crossing.
- *C* and *D* are possible solutions, *C* is minimum difference from *B*.

The Labeling Search

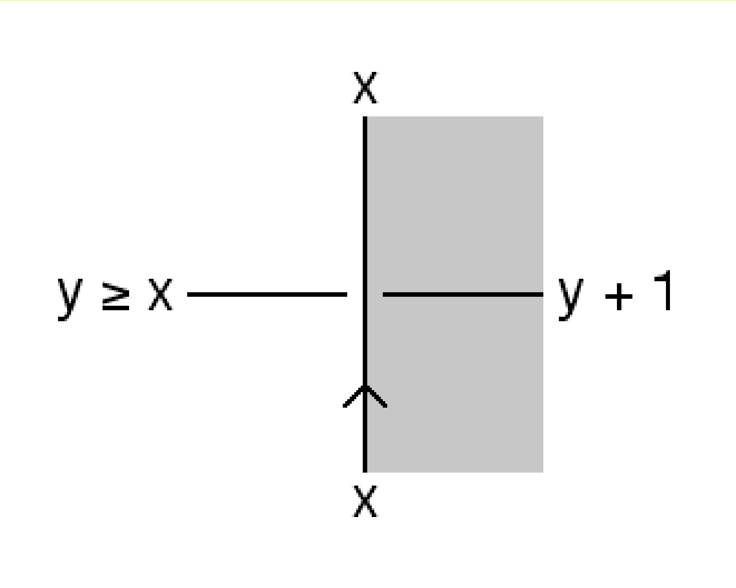
- Branch-and-bound
- Constraint propagation
- Iterative deepening
- Timeouts

Branch-and-bound

- Search goal: ***minimum difference labeling***
- Node expansion can never decrease the accumulated labeling difference
- Minimum difference legal solution gives the bound
- Search is truncated when the accumulated current difference exceeds the bound

Constraint Propagation (Waltz '75)

- Orders the search so that legal solutions are found earlier



- Legal solutions define bounds
- Constraint propagation works in concert with branch-and-bound to increase search efficiency

Waltz, D. L., Understanding line drawings of scenes with shadows, McGraw-Hill, New York, pp. 19-92, 1975.

Iterative Deepening

- Branch-and-bound works best if good solutions are found earlier
- In good solutions, changes are localized to the ***area of interest***
- Search is restarted with increasing ***search horizons***

Timeouts

- The search can take too long
- Two timeouts:
  - ***Very short timeout (0.1 sec)***: If a solution has been found during the search
  - ***Longer timeout (5.0 sec)***: If no solution has been found yet

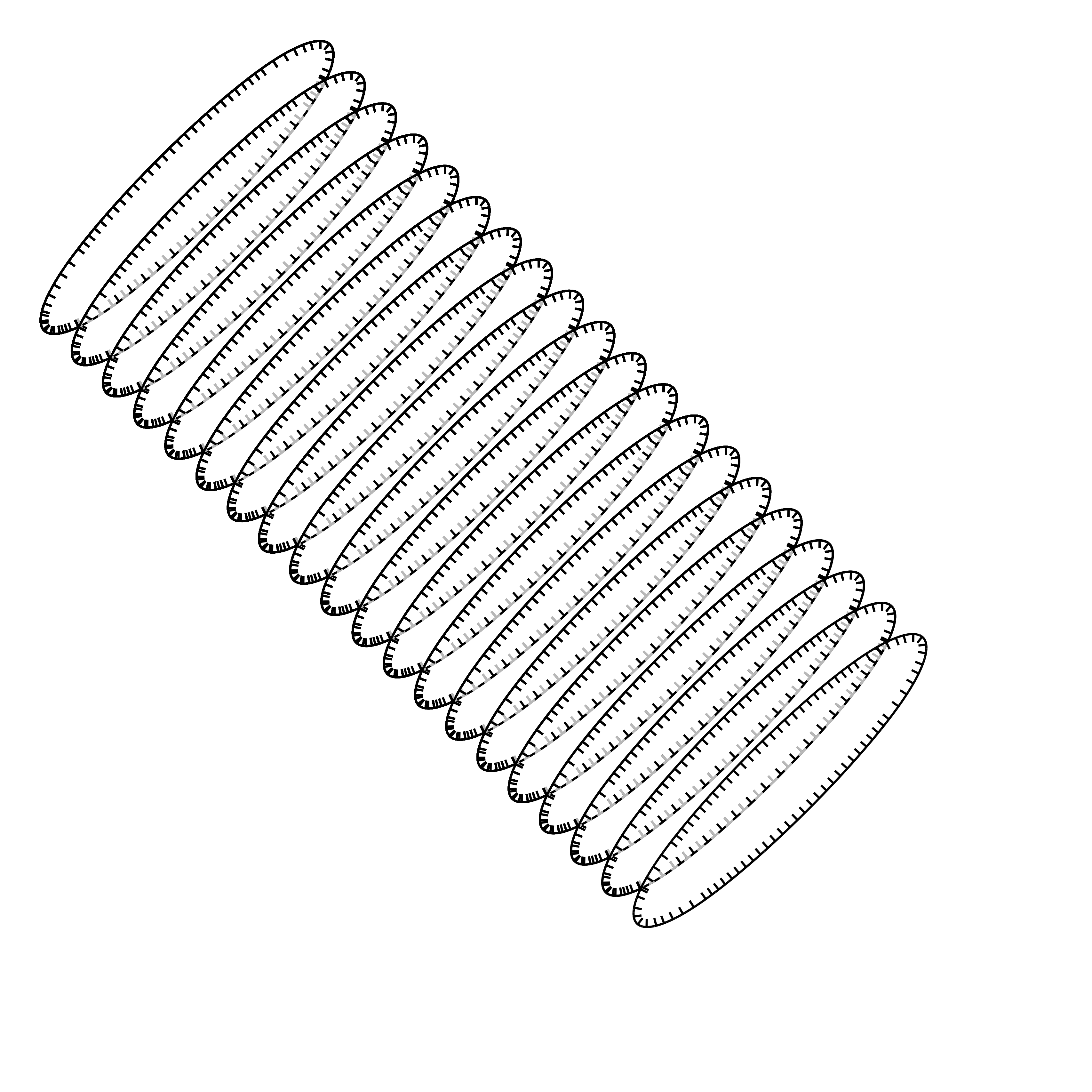
Measuring Drawing Complexity

- Total number of crossings
- Maximum depth

Experiments: Two Labeling Methods

- Randomized labeling
- Incremental labeling

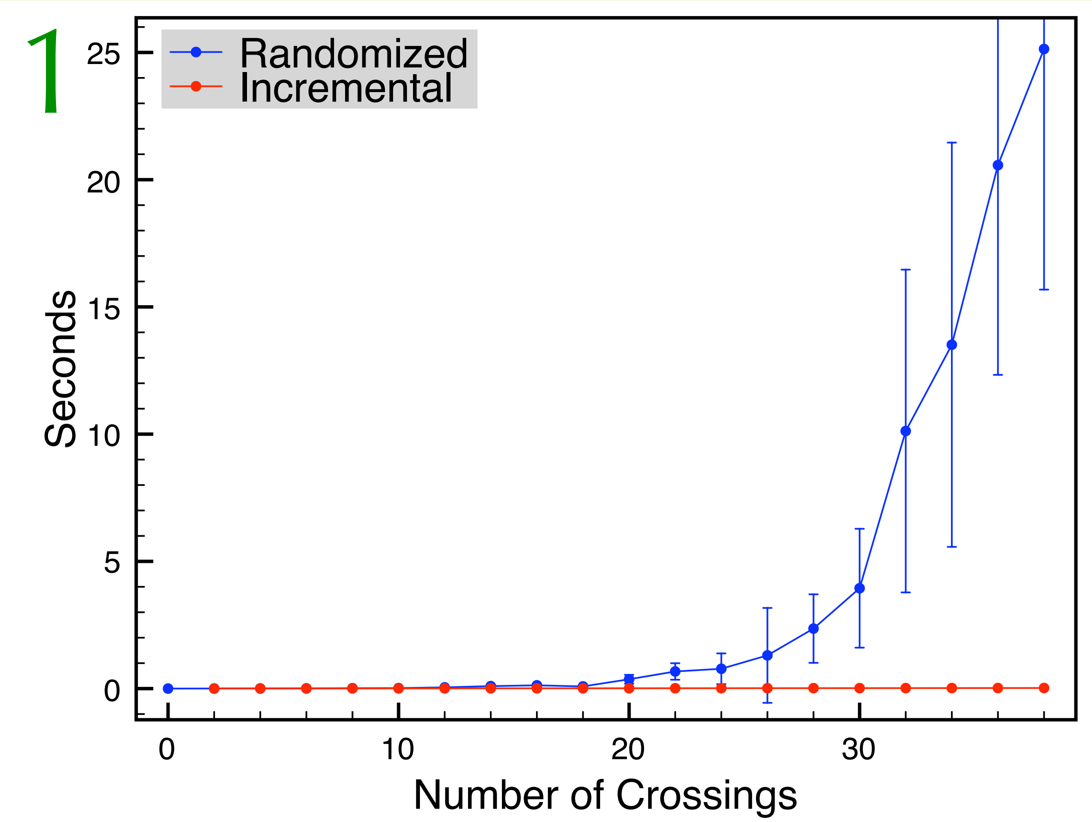
Test 1

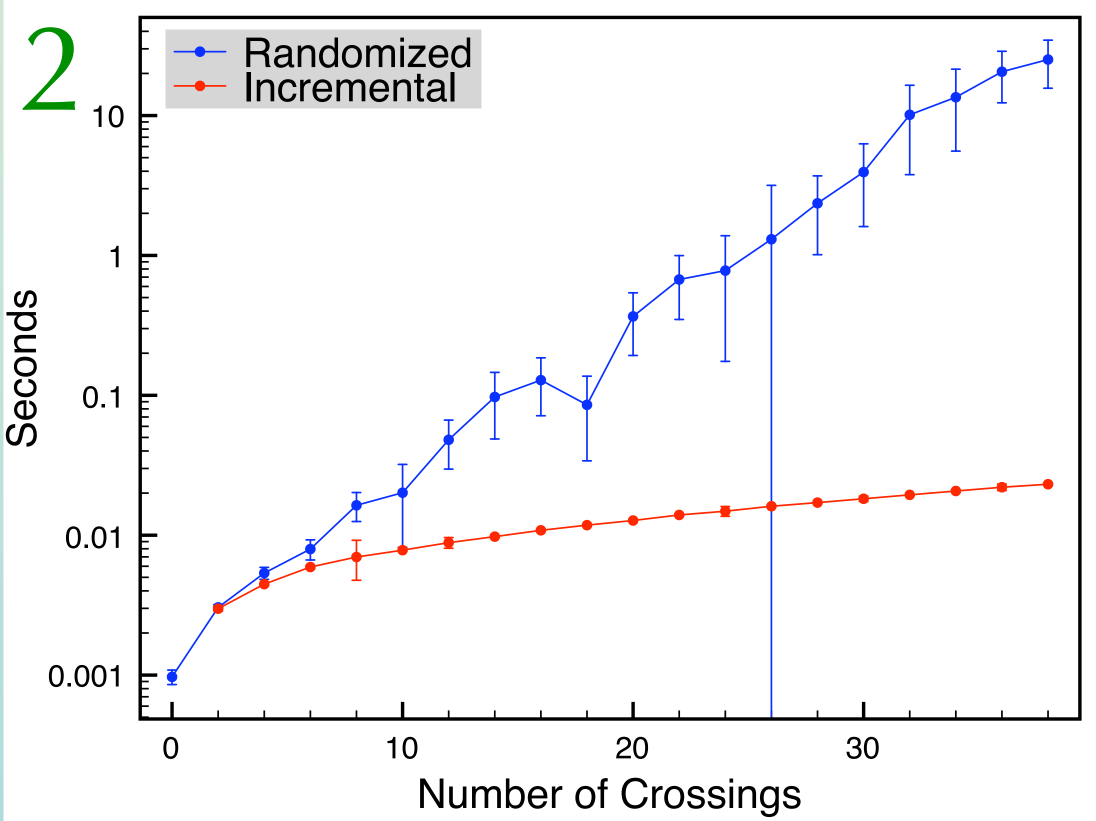


- **Number of crossings**: linear in the number of surfaces
- **Max depth**: constant

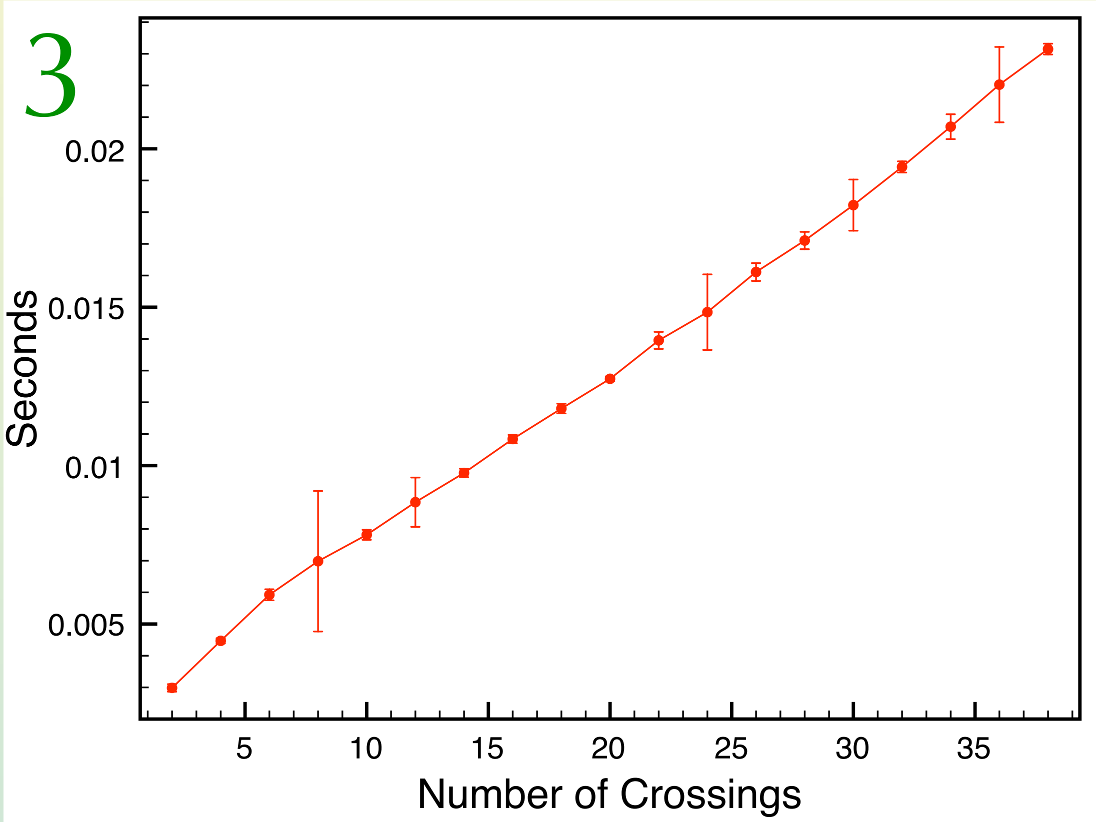
Test 1: Labeling Time vs. # Crossings

Running time vs. # Crossings

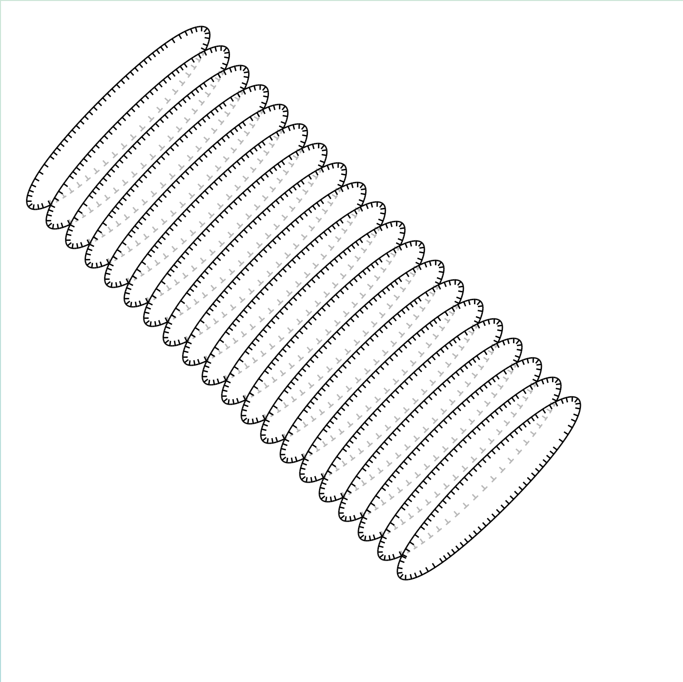




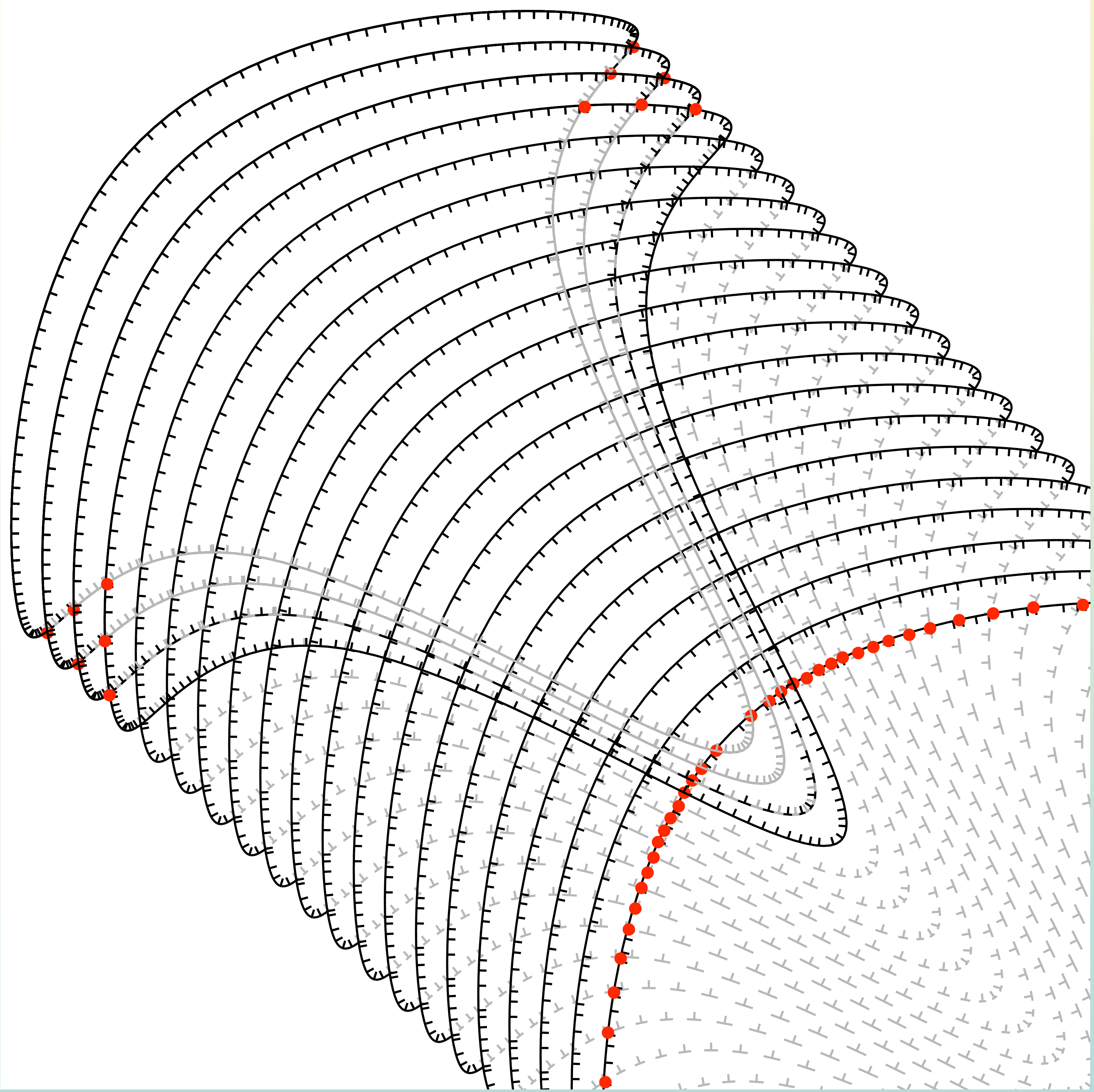
Running Time vs. # Crossings
(Incremental Labeling)



Running time vs.
Crossings
(log Y axis)



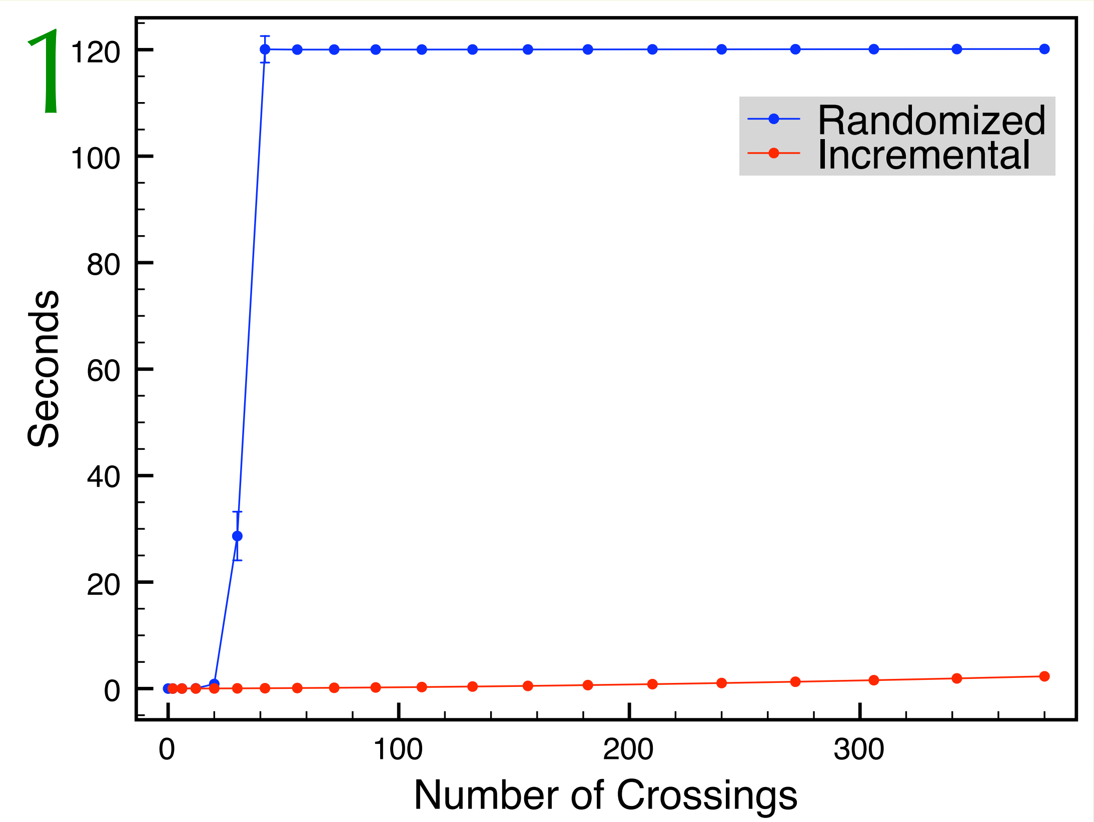
Test 2

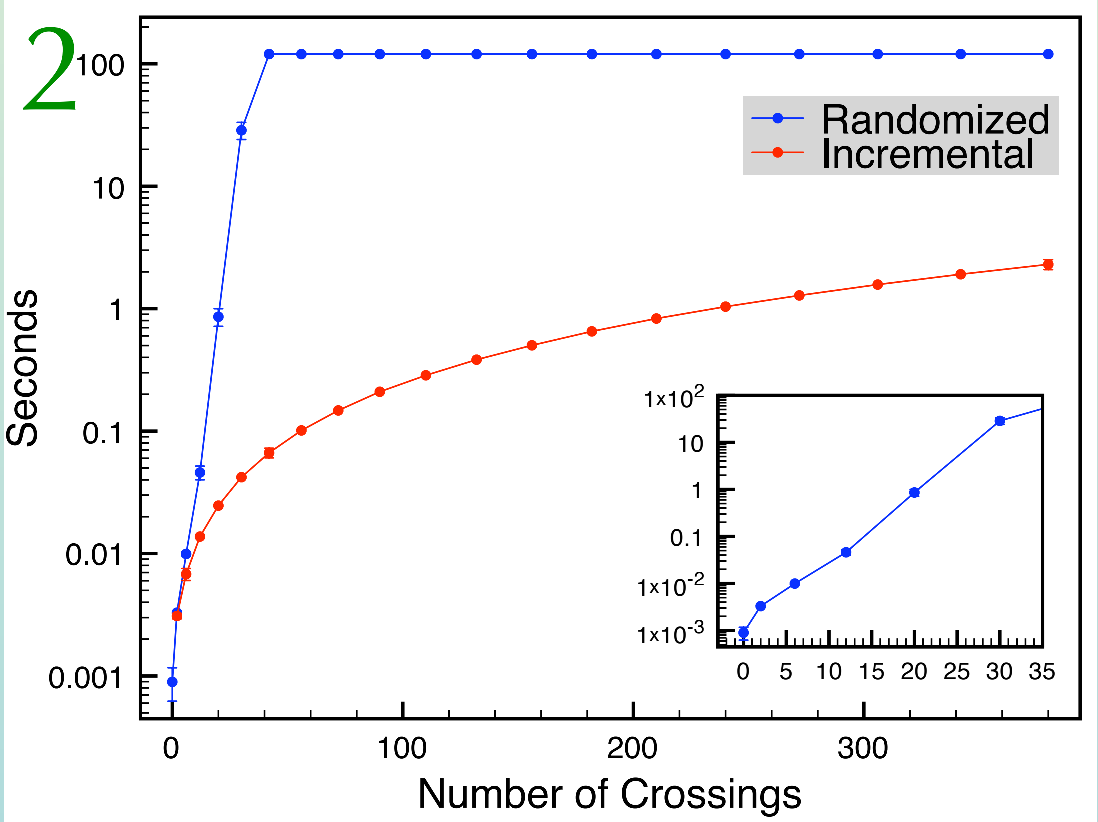


- **Number of crossings**: quadratic in the number of surfaces
- **Max depth**: linear in the number of surfaces

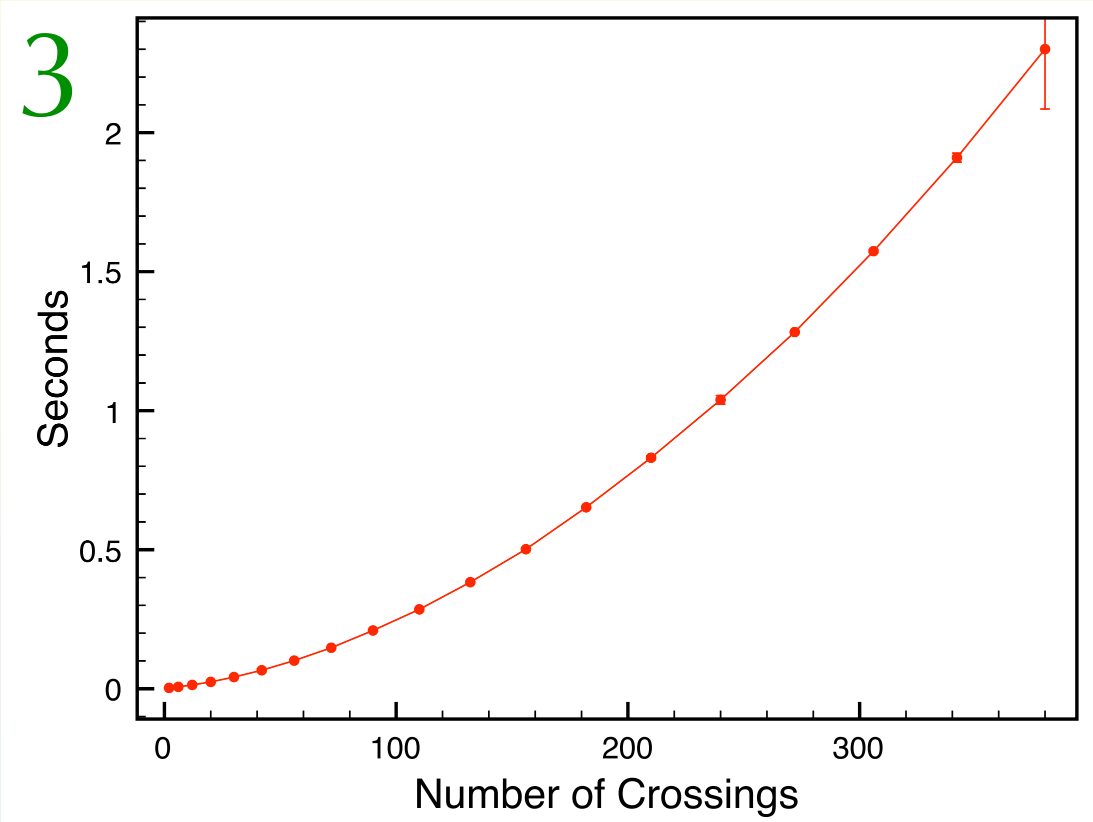
Test 2: Labeling Time vs. # Crossings

Running time vs. Number of Crossings

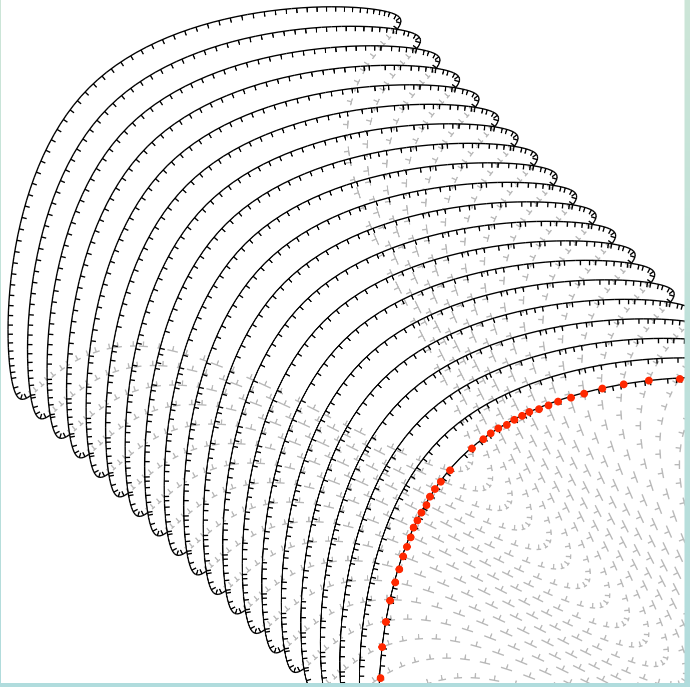




Running Time vs. Number of Crossings
(Incremental Labeling)

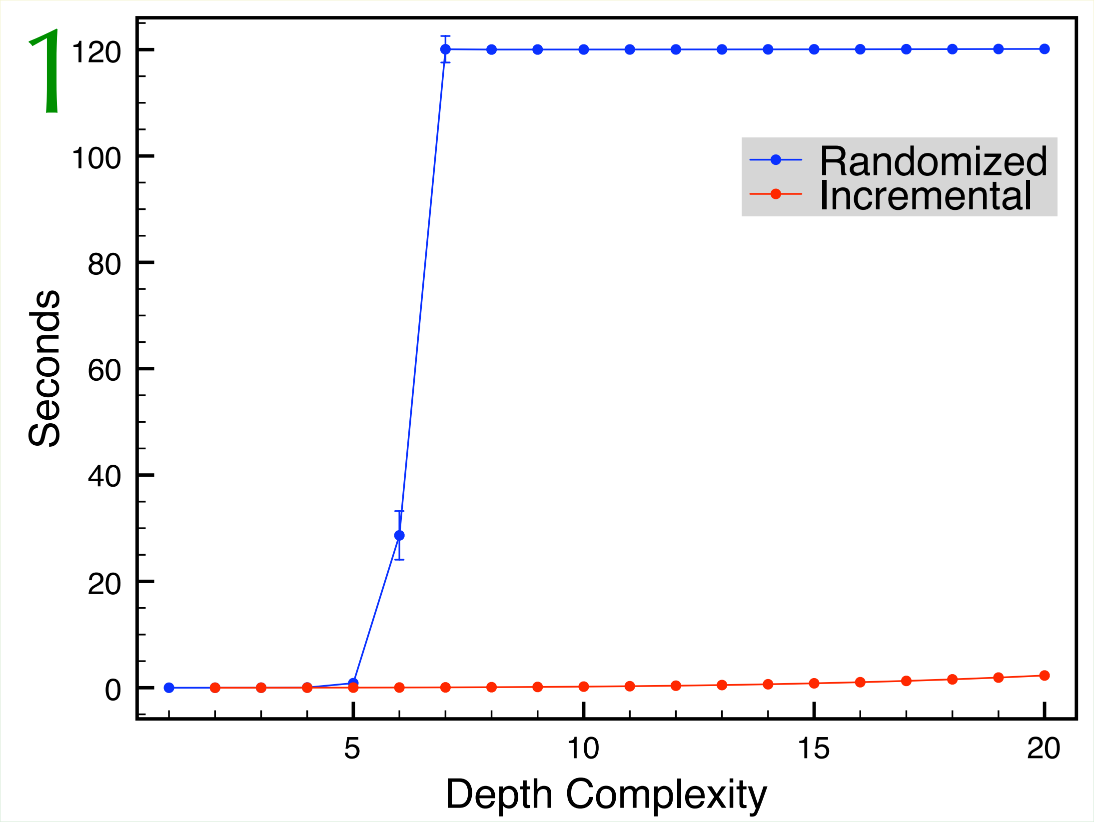


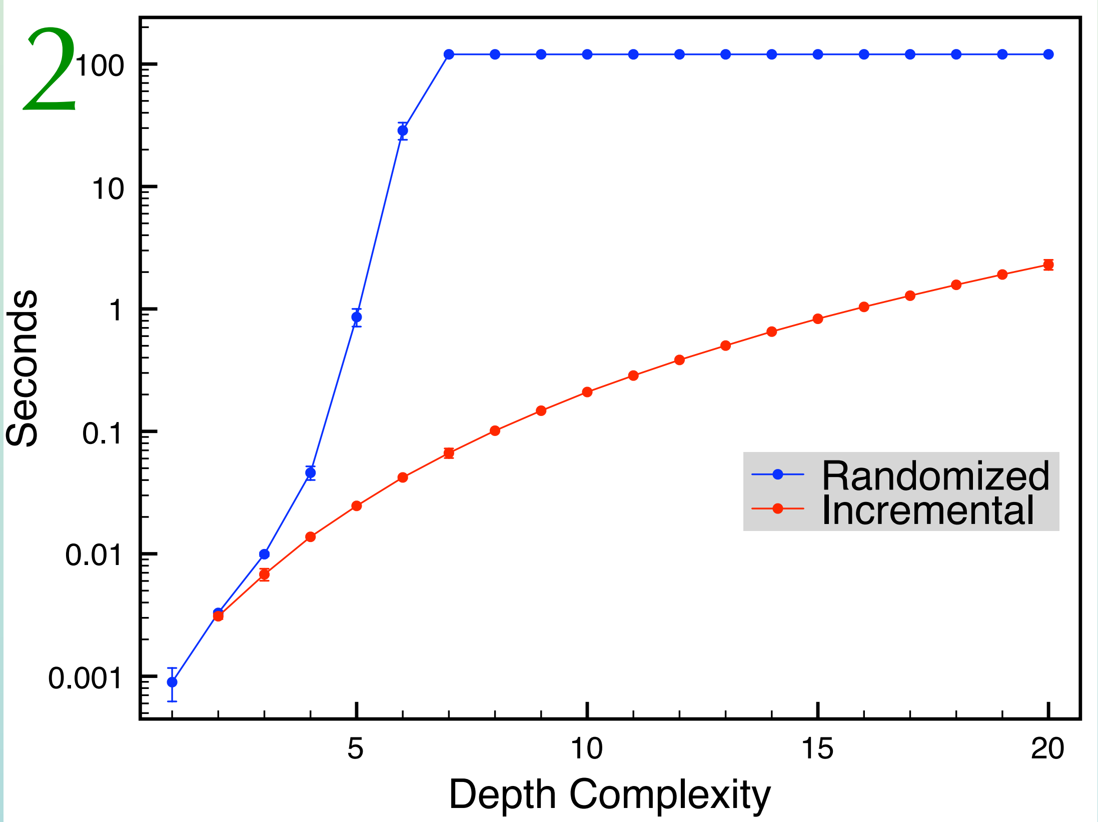
Running time vs.
Number of Crossings
(log Y axis)



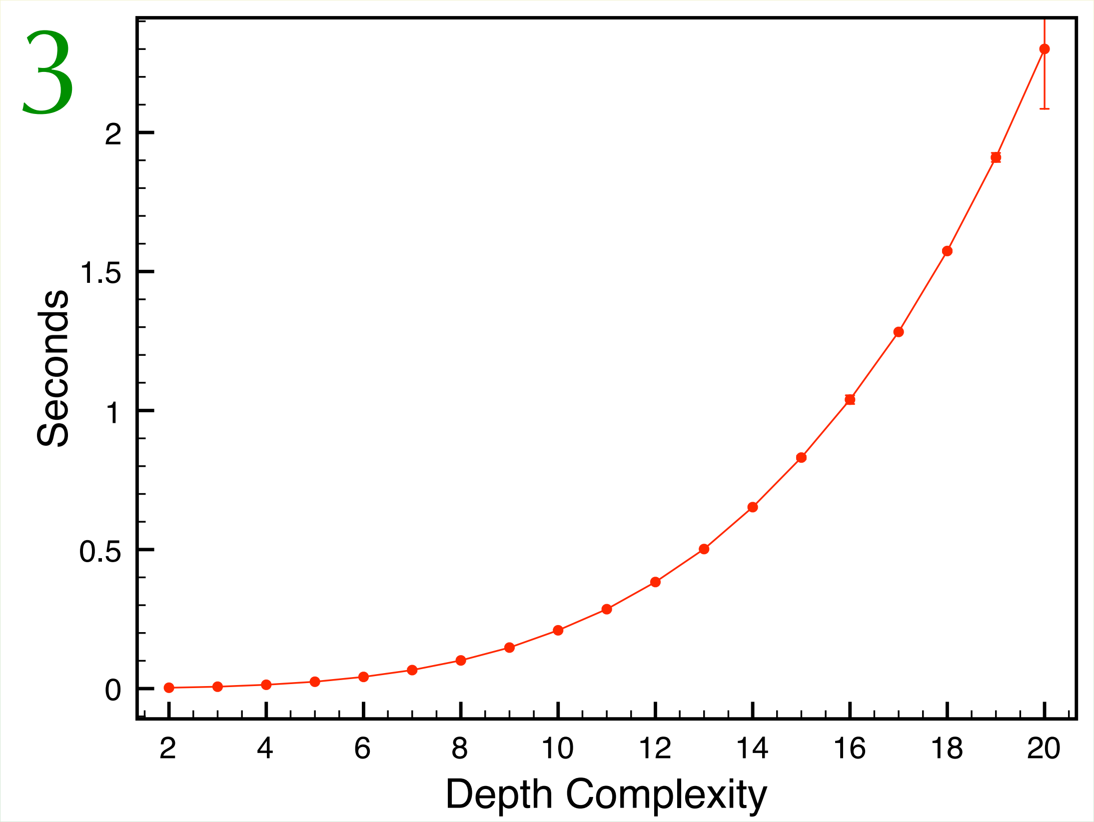
Test 2: Labeling Time vs. Max Depth

Running time vs. Max Depth

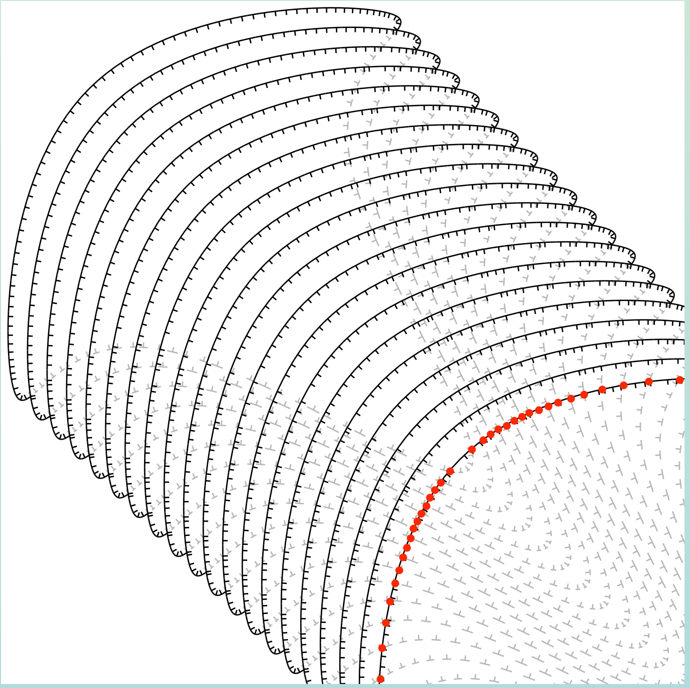




Running time vs. Max Depth

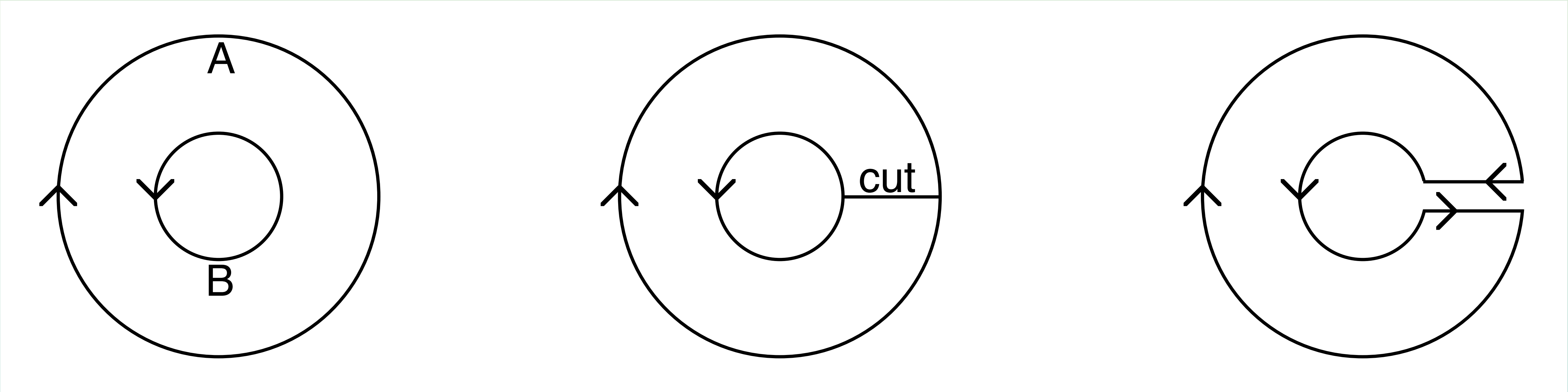


Running time vs.
Max Depth
(log Y axis)



Boundary Grouping with Cuts

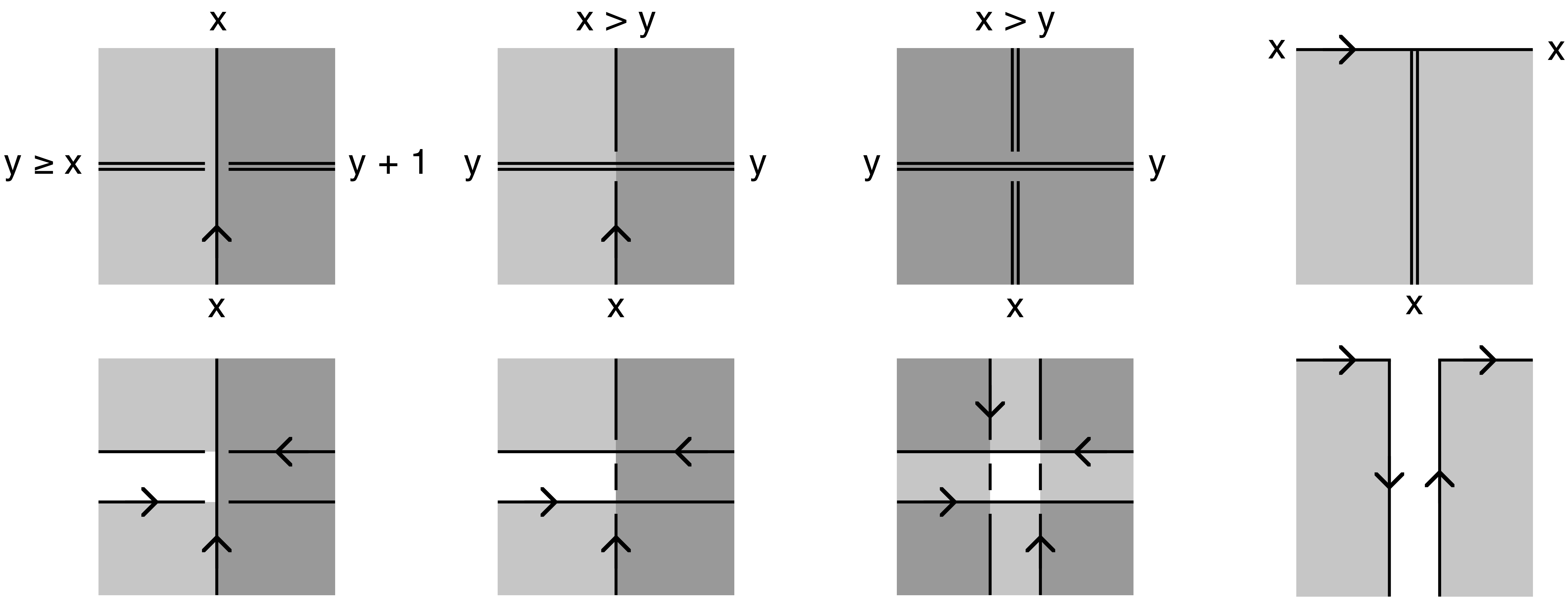
- Some surfaces have multiple boundaries
- This can cause problems
- A ***cut*** between two different boundaries reduces the number of boundaries by one



Cuts are a geometric device. Needn't be horizontal or straight.

Cut Labeling Schemes

Using cuts requires four new labeling schemes



1 A boundary crosses a cut with the boundary above

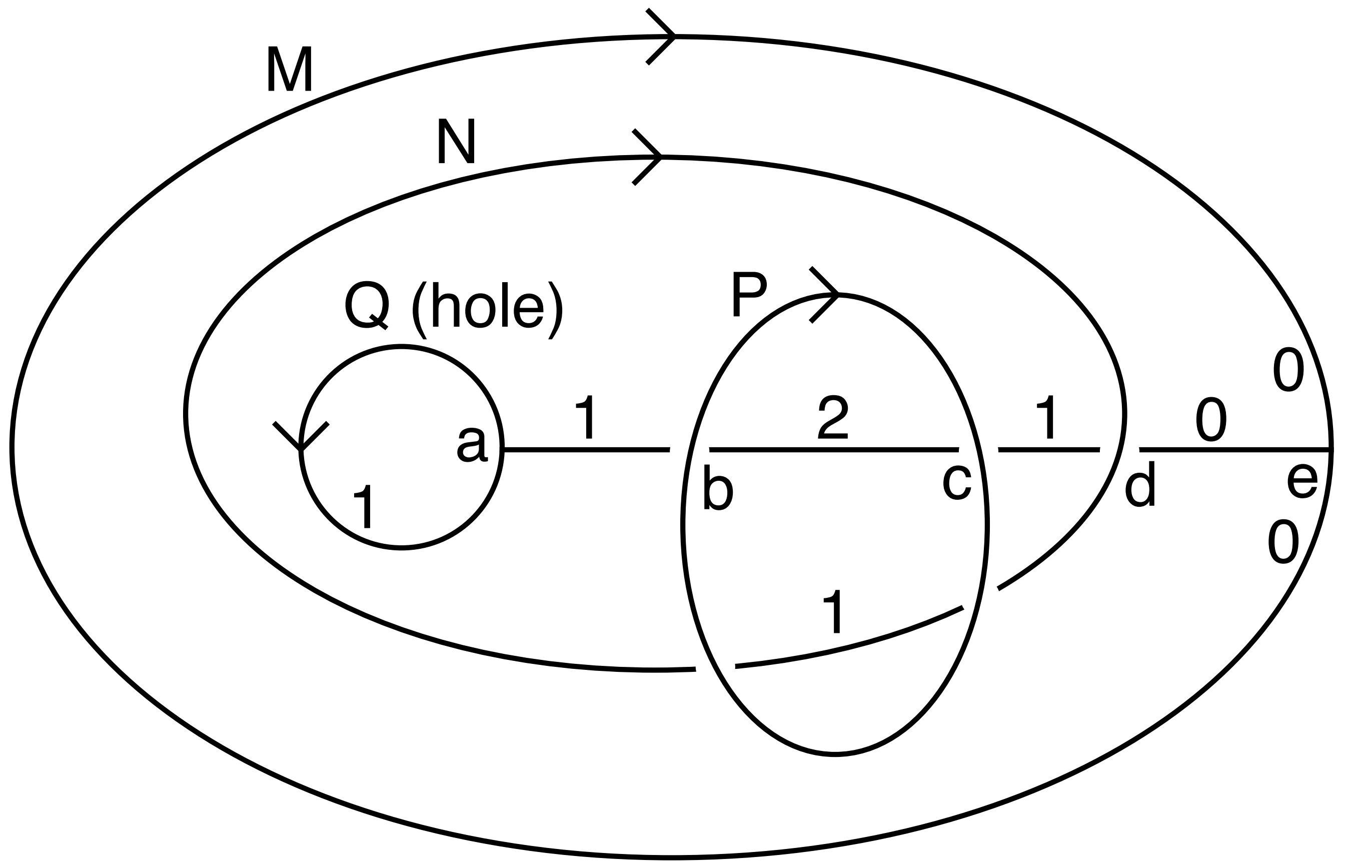
2 A boundary crosses a cut with the boundary below

3 A cut crosses a cut

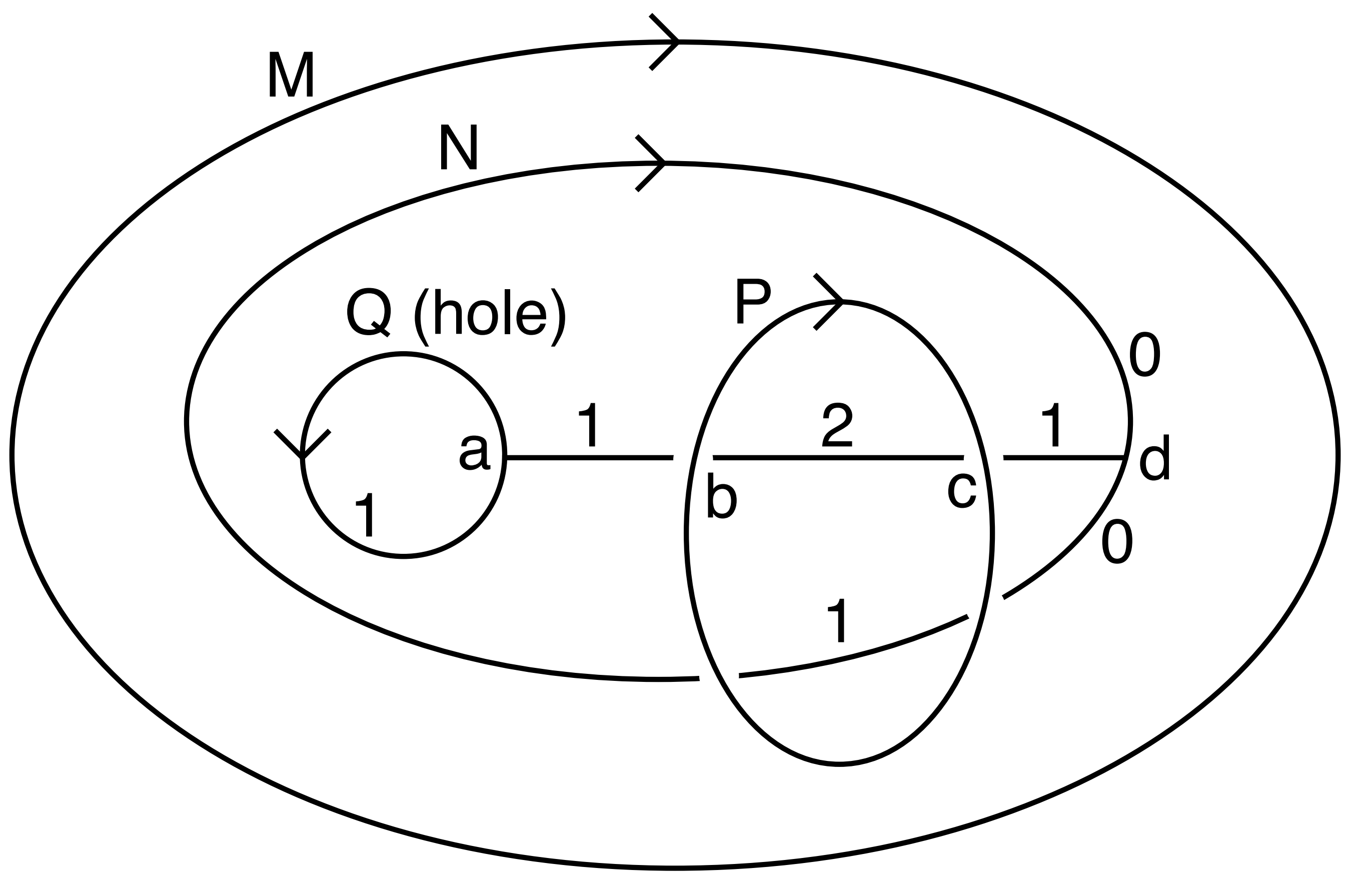
4 A cut *ends* and attaches to a boundary, *i.e.*, a *T-junction*

Cuts denoted with a double line (top row) and a gap (bottom row)

Finding Legal Cuts



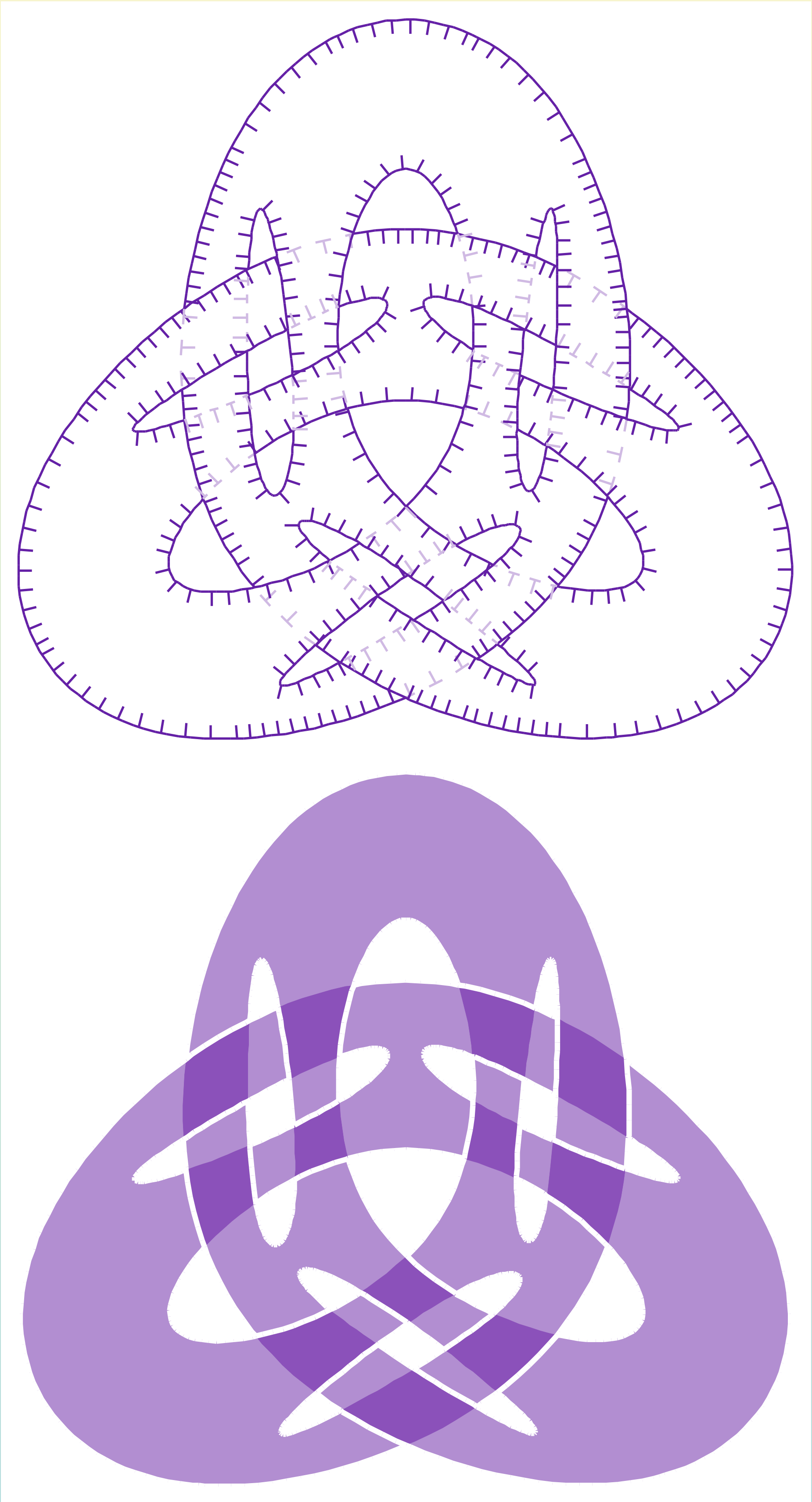
A successful cut: Last crossing (*e*) is legal.



An unsuccessful cut: Last crossing (*d*) is illegal.

Rendering

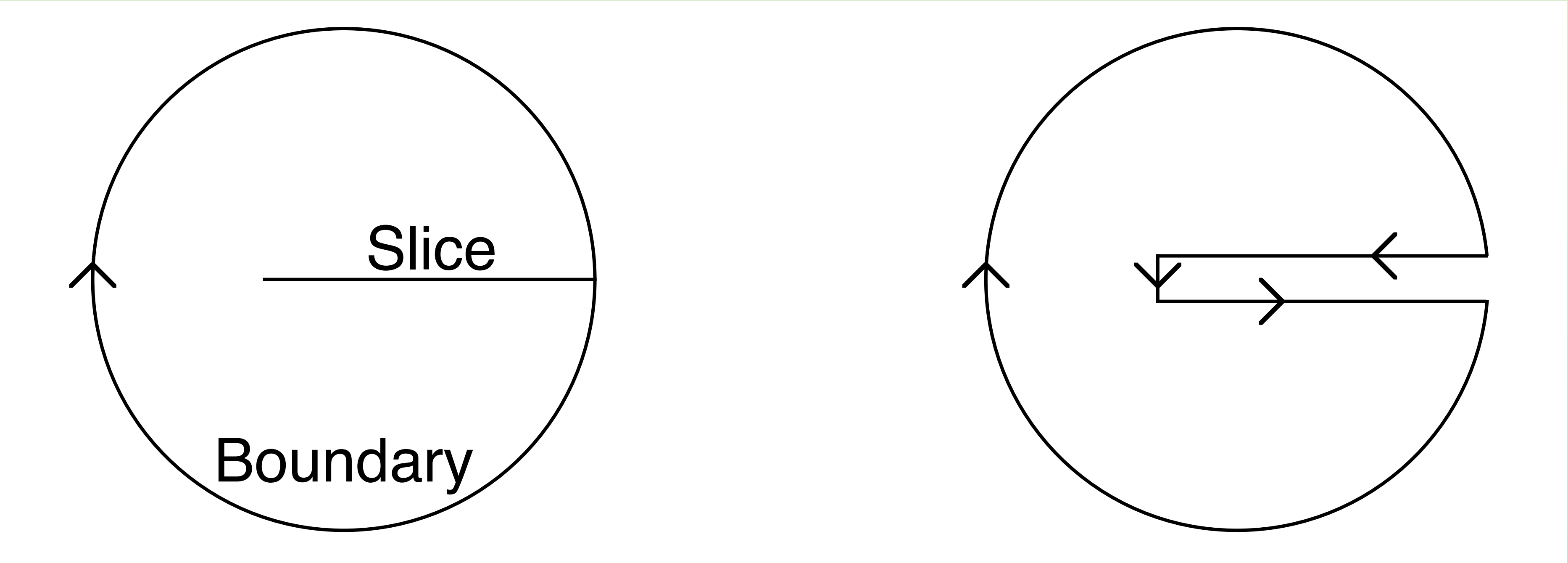
- Conversion of a labeled knot-diagram to an image with solid fills
- Requires full depth ordering of all surfaces covering each region
- *Druid* uses the ***episcotister model*** (Metelli '74)



Metelli, F., The perception of transparency, Scientific American, 230(4), pp. 90-98, 1974.

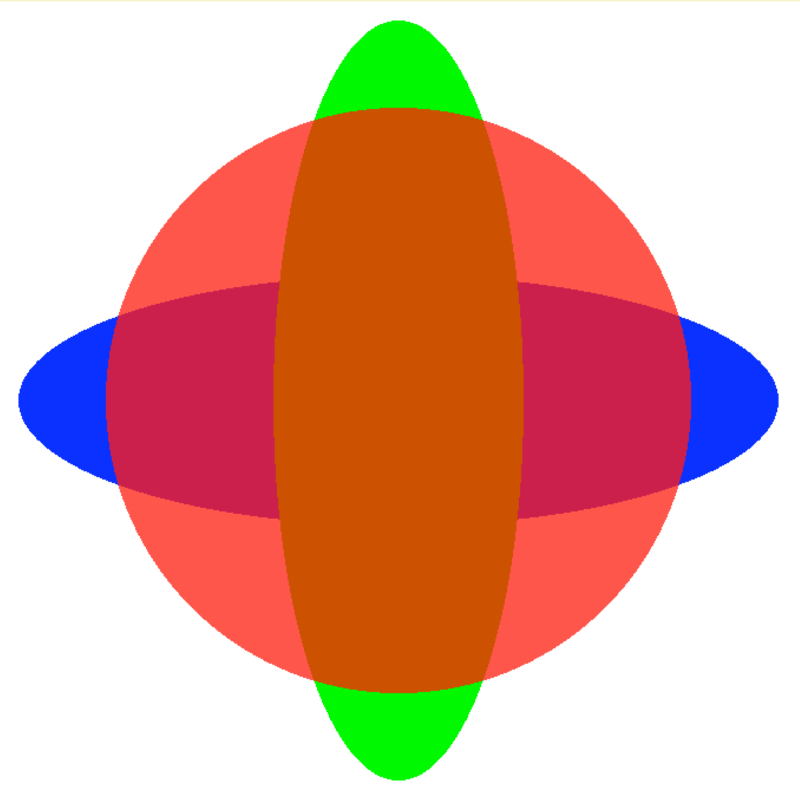
Slice

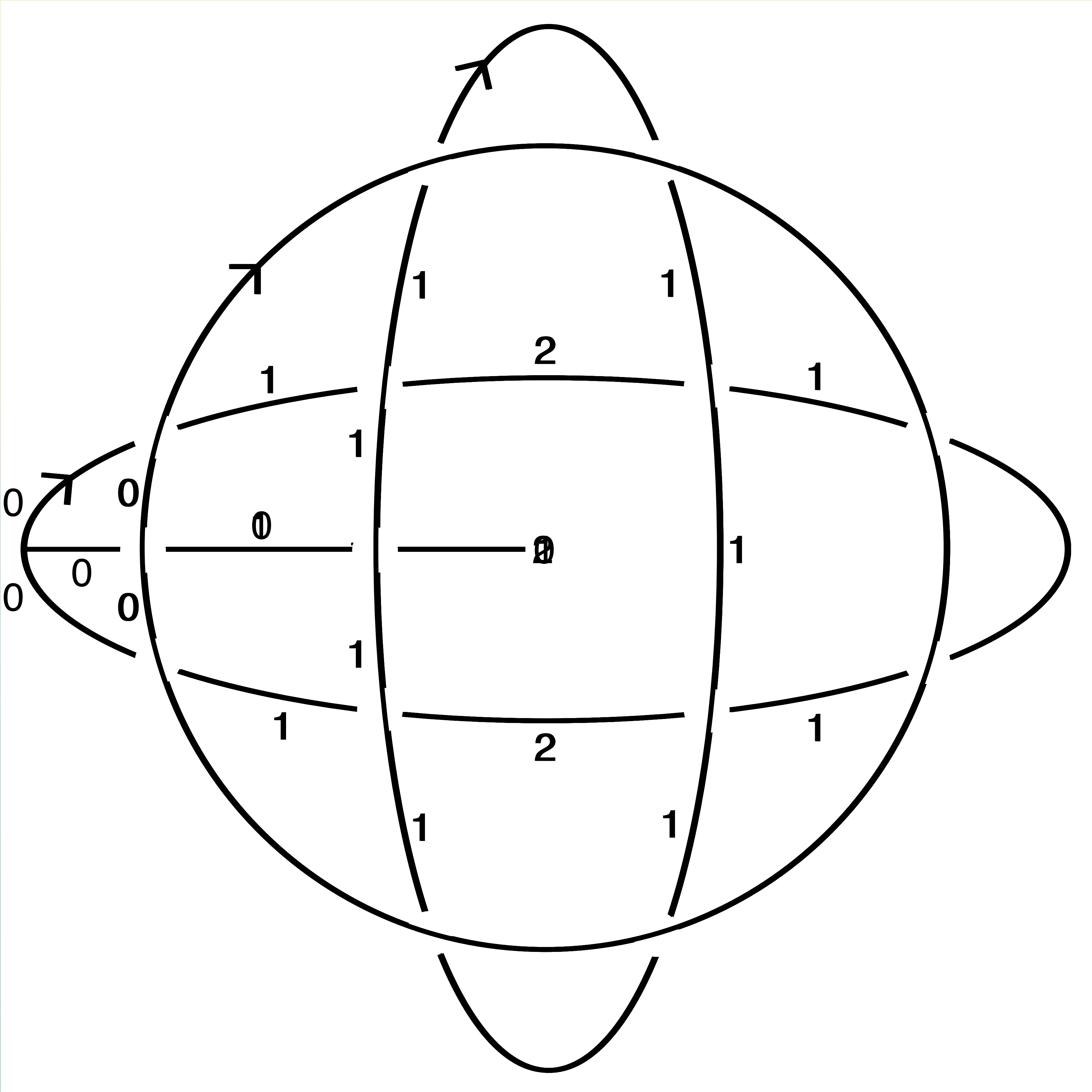
- A ***slice*** connects a location on a boundary to a point within the bounded surface
- Similar to a cut



Slices are a geometric device. Needn't be horizontal or straight.

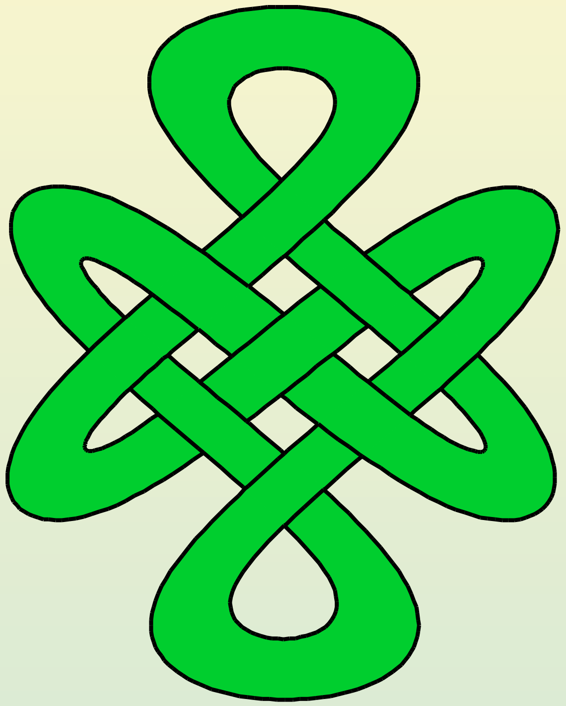
Using Slices to Find Region Coverings

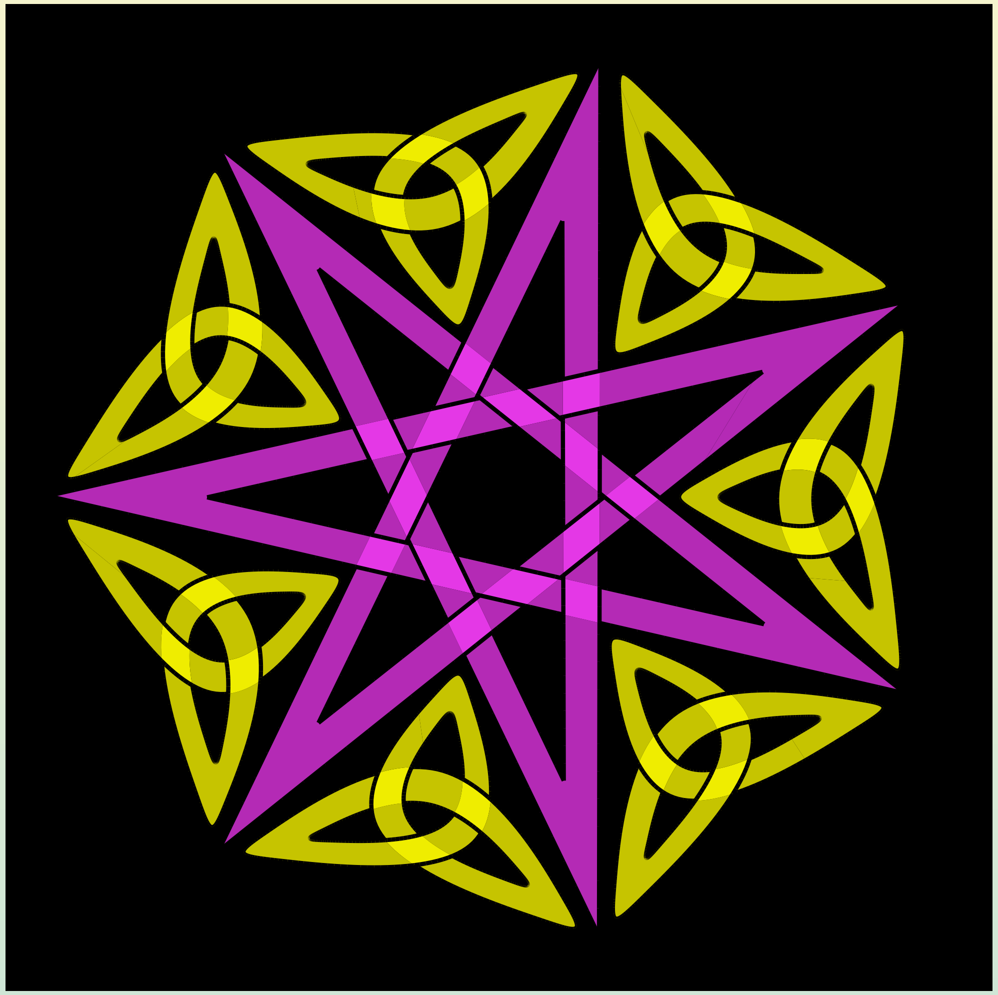


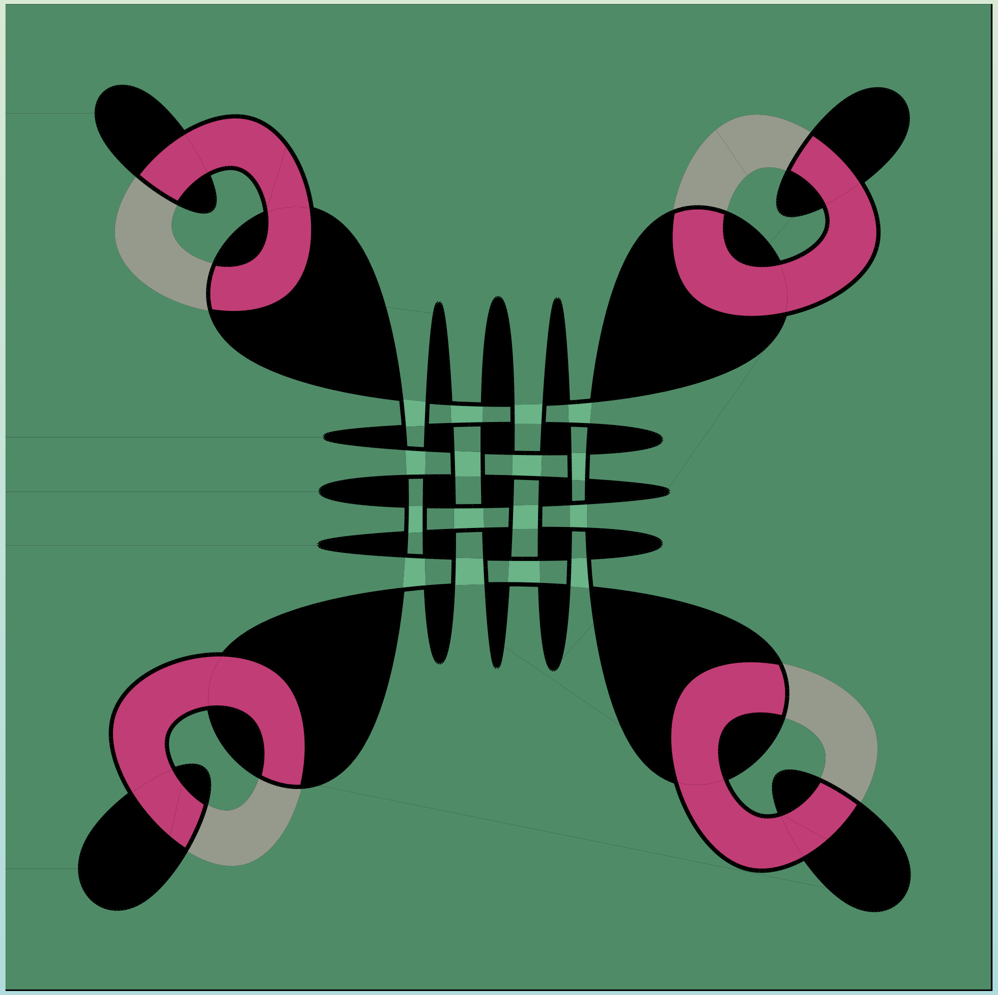


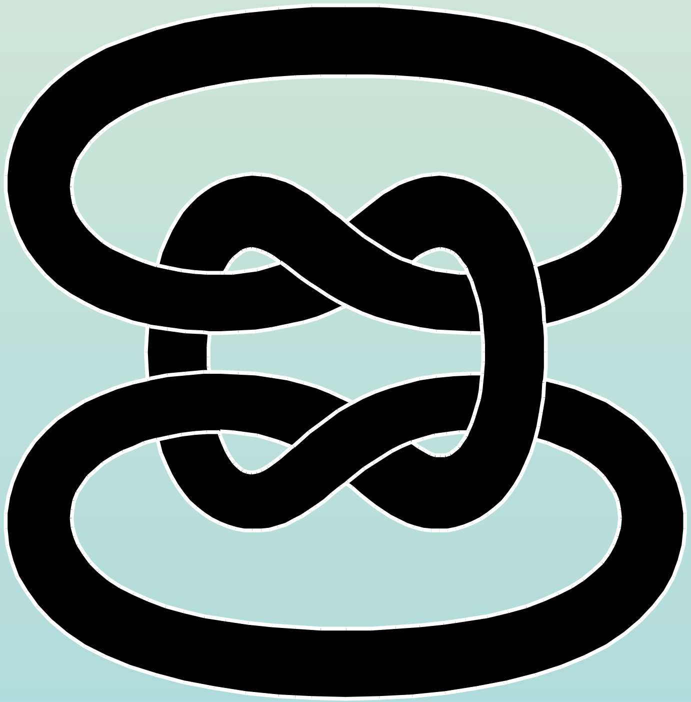
Red is above green, which is above blue

Druid Examples









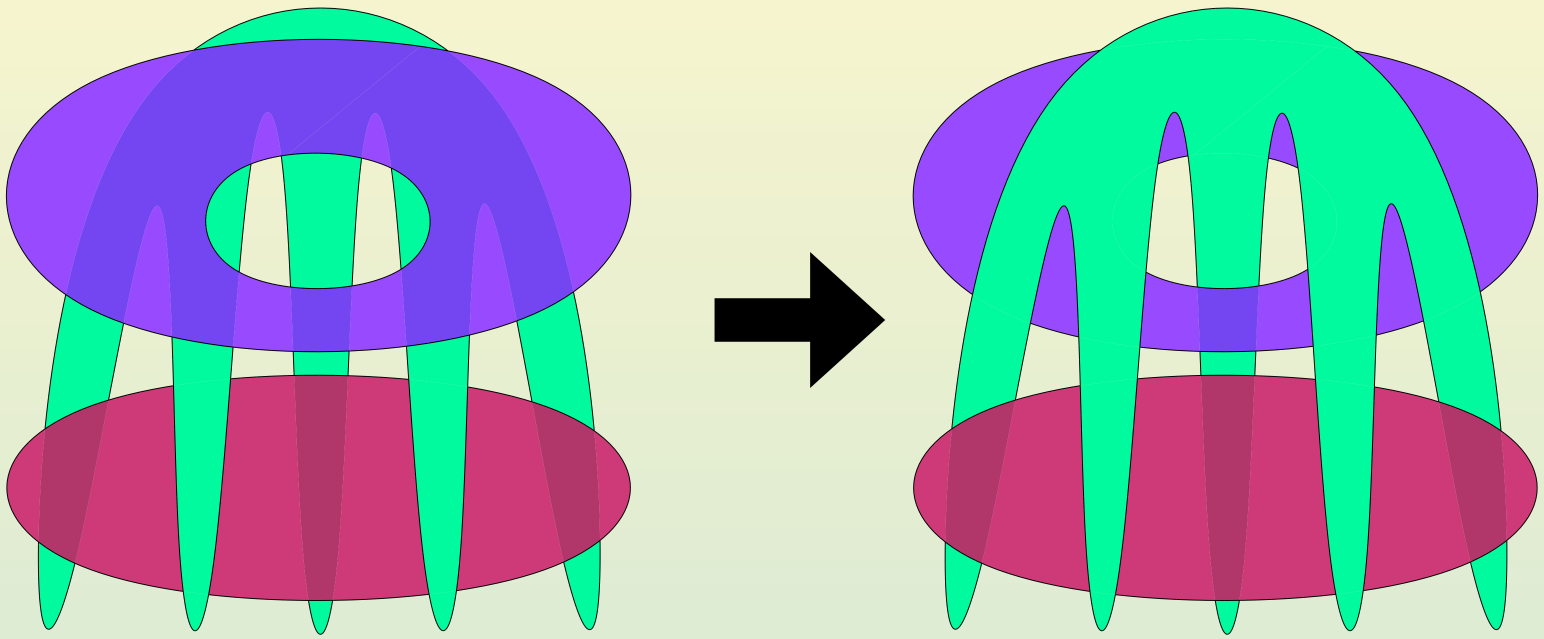
A Problem with the Search

- Search space size: 2^C for C crossings
- A drawing can have hundreds of crossings.
- The search takes too long for complex drawings.
- Thus, *Druid* as described in (Wiley and Williams ‘06a) was limited.

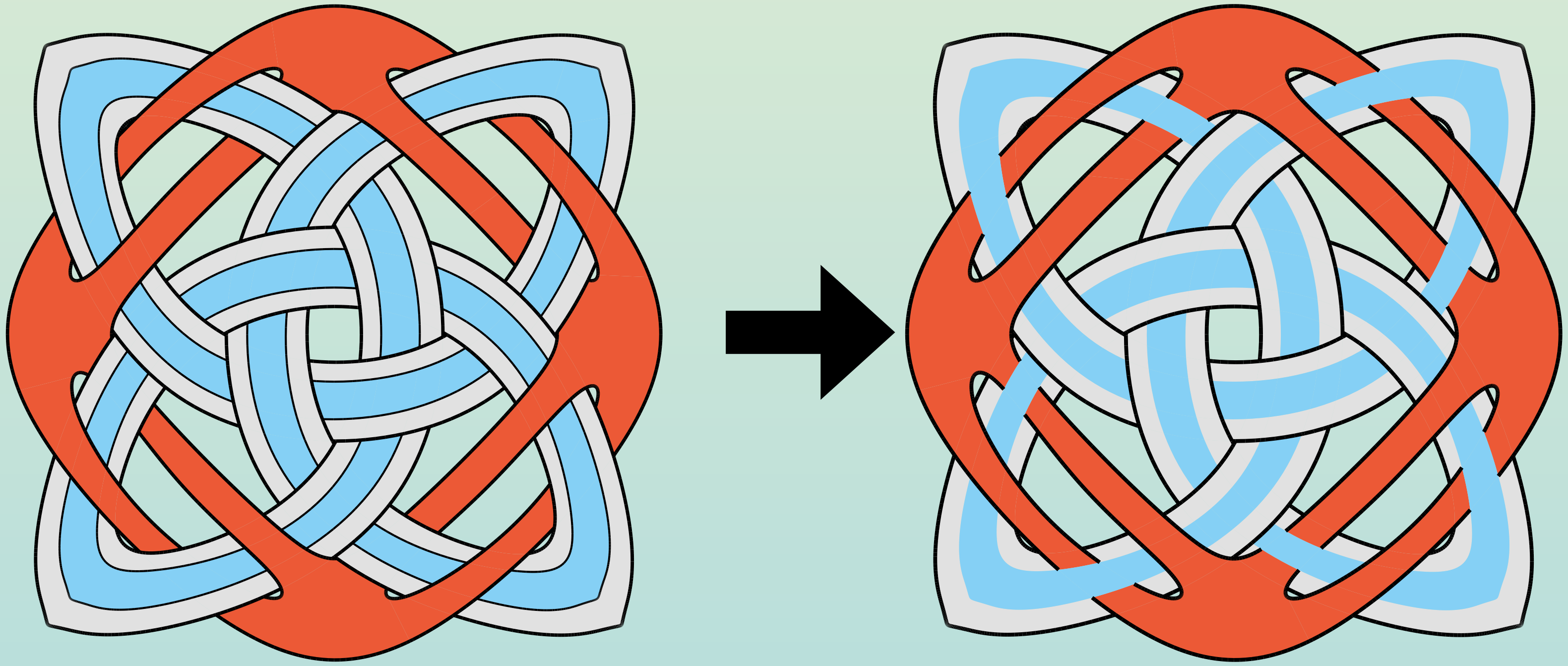
Wiley, K. B., Williams, L., 2006. Representation of Interwoven Surfaces in 2 1/2 D Drawing. *Proc. of CHI*, Conference on Human Factors in Computing Systems, Montreal, Canada, 2006.

A Problem with the Search (contd.)

Druid fails to label this flip in under 120 seconds in 50% of tests



Druid takes 35 seconds on average to perform one of these flips (and fails in 2% of tests)

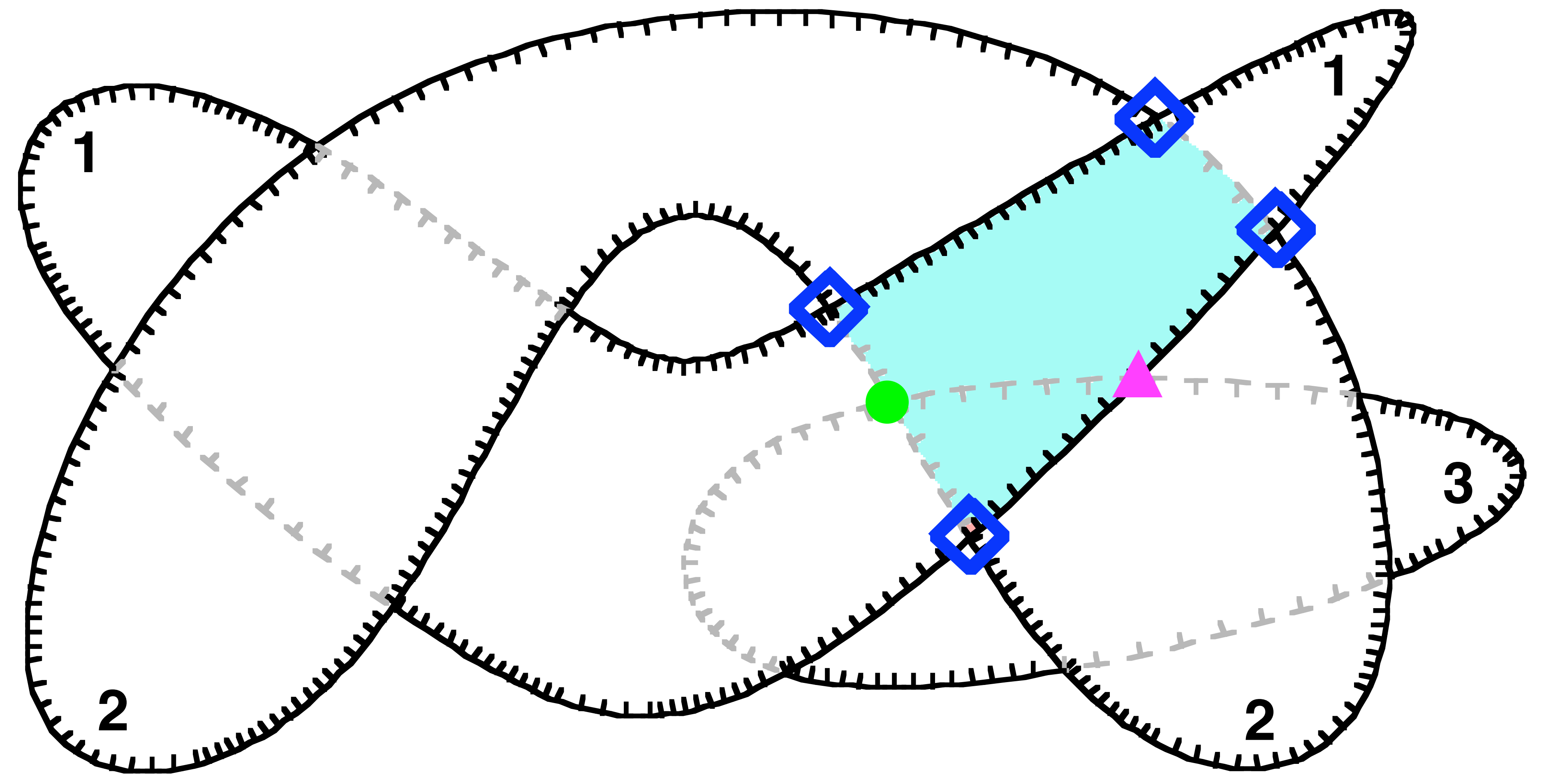


Crossing-State Equivalence Class Rule

- Discovered a property of 2½D scenes, the ***crossing-state equivalence class (CSEC) rule***
- Use this property to improve performance

Area of Overlap

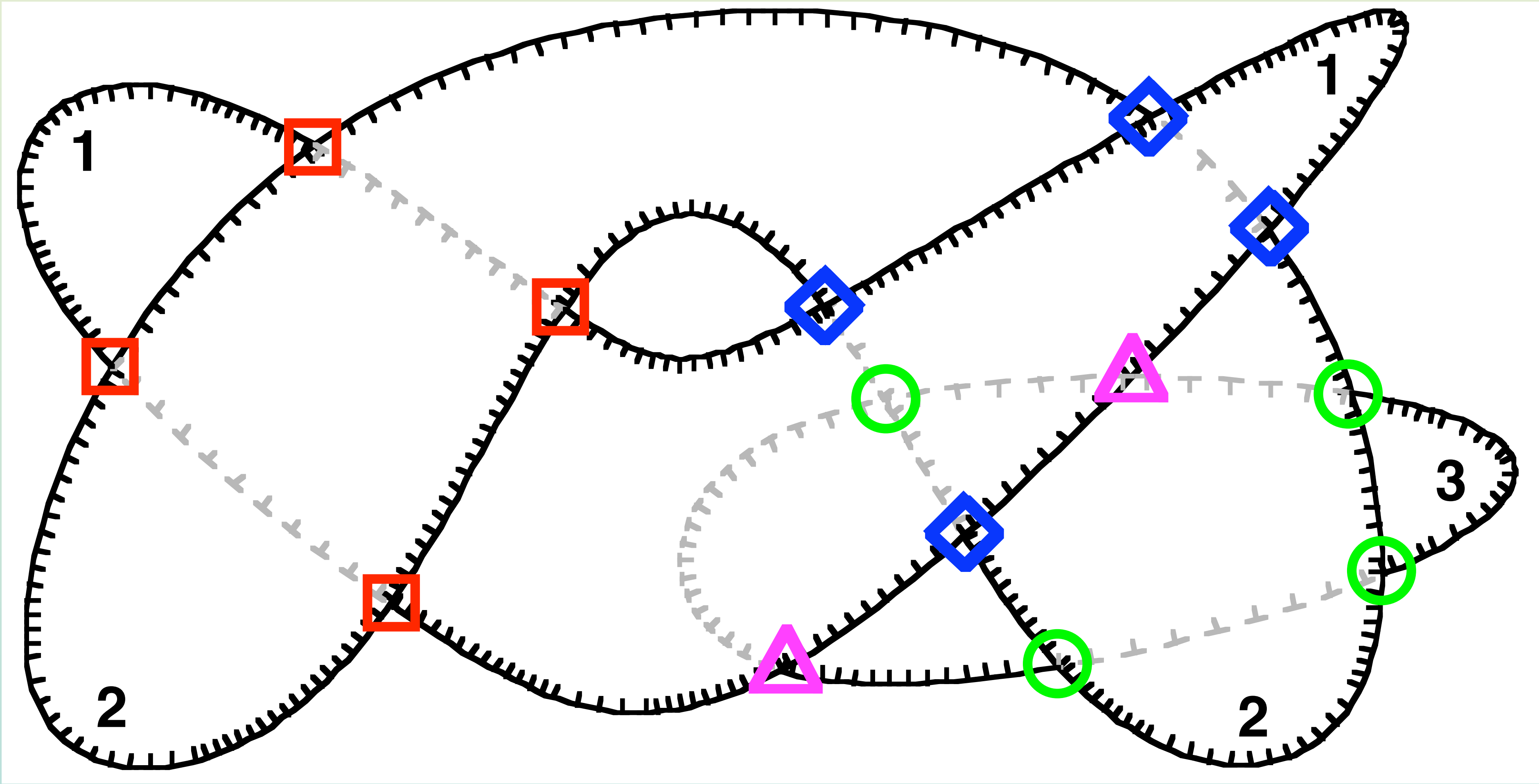
Numbers label unique surfaces



- ***Area of overlap***: The maximum contiguous area where two surfaces overlap, *e.g.*, the shaded area for surfaces *1* and *2*
- ***Corner***: A crossing where a traversal of an *area of overlap's* border switches boundaries, *e.g.*, the blue diamonds for the shaded area

Crossing-State Equivalence Class (CSEC)

The corners of an area of overlap

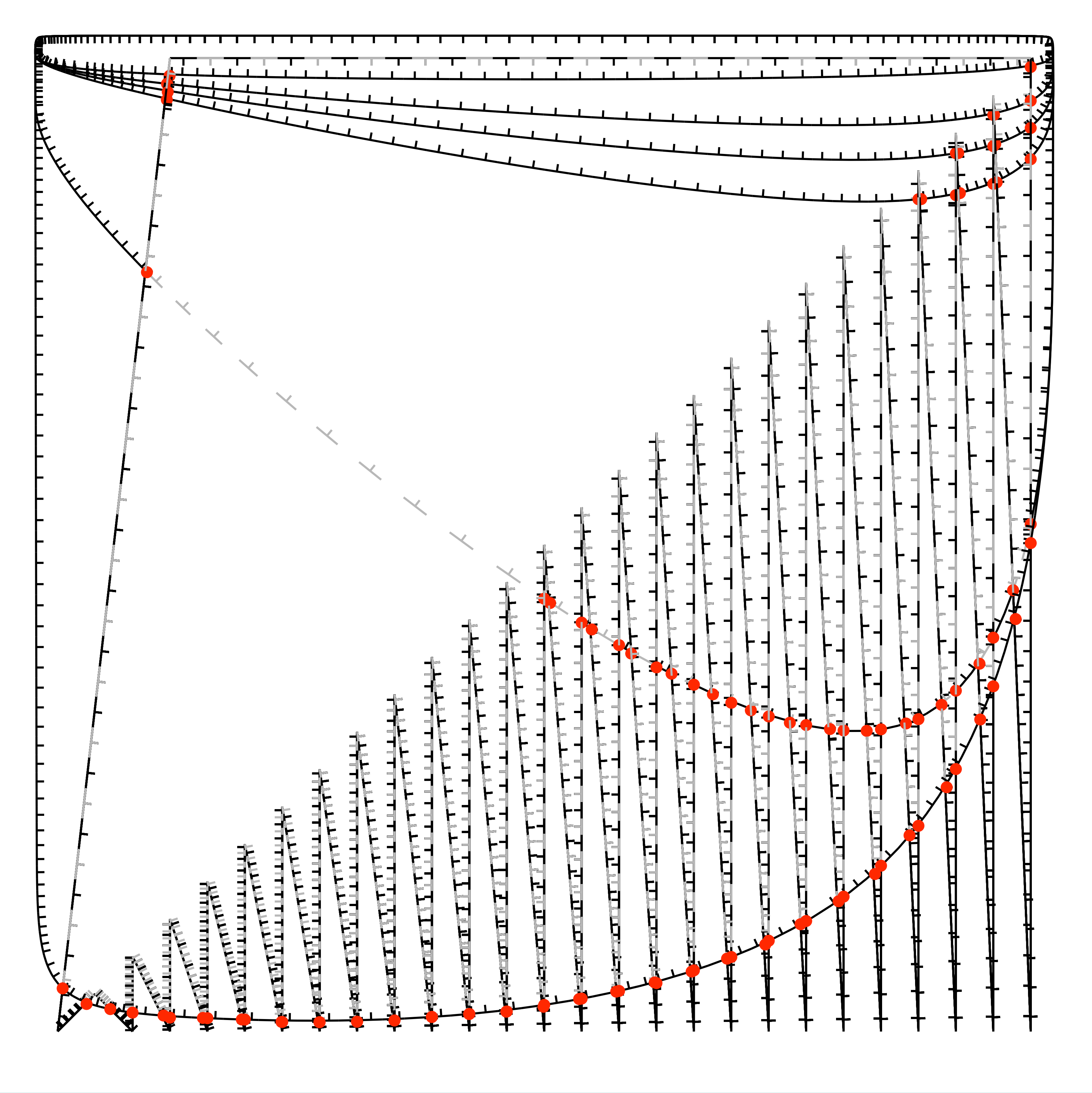


Unique shapes/colors indicate CSECs

Finding CSECs on Labeled Figures

- Intend to use CSECs to improve performance
- But *Druid* must ***find*** the CSECs before they can be used
- How long does this take? Does it cancel the benefit of using CSECs in the first place?

Finding CSECs on Labeled Figures

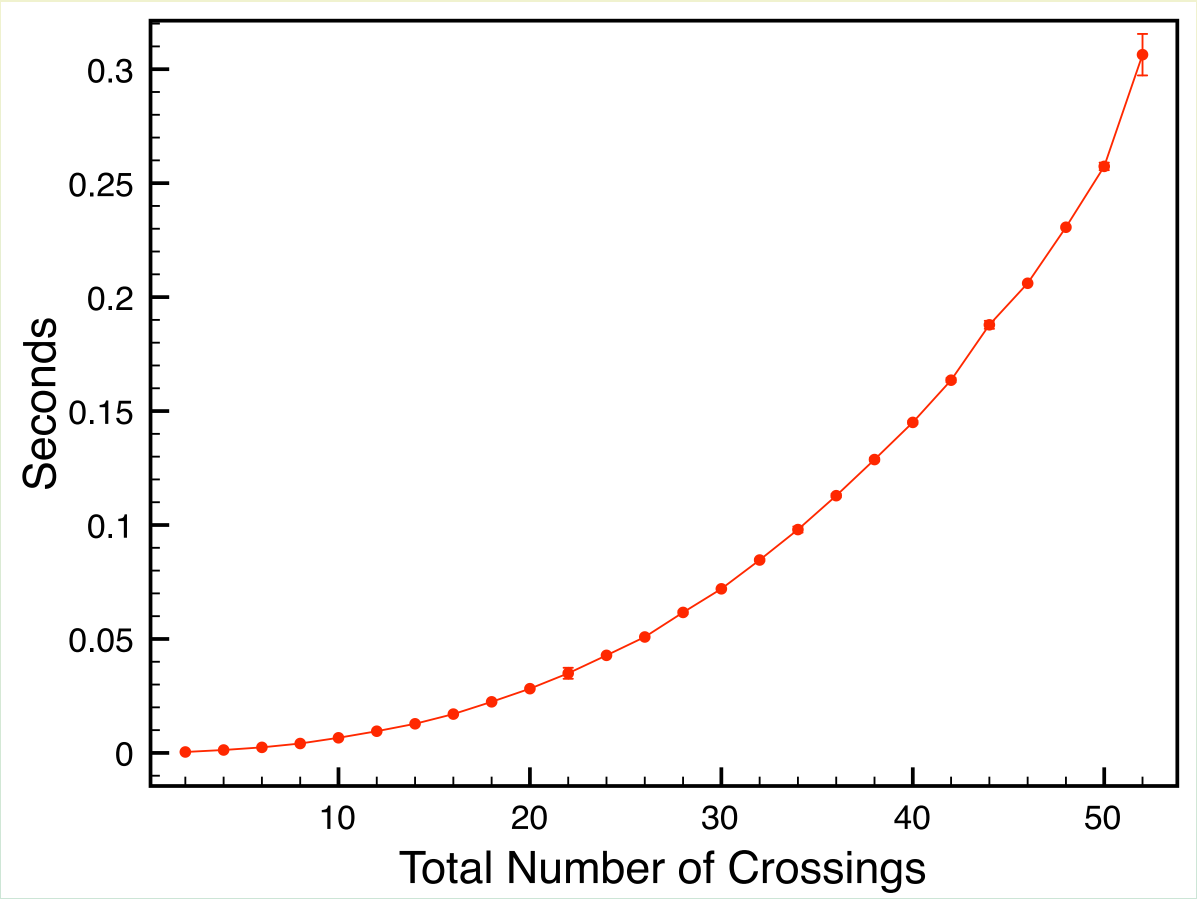


Experiment: Across a spectrum of CSEC sizes, measure the time required to find all CSECs.

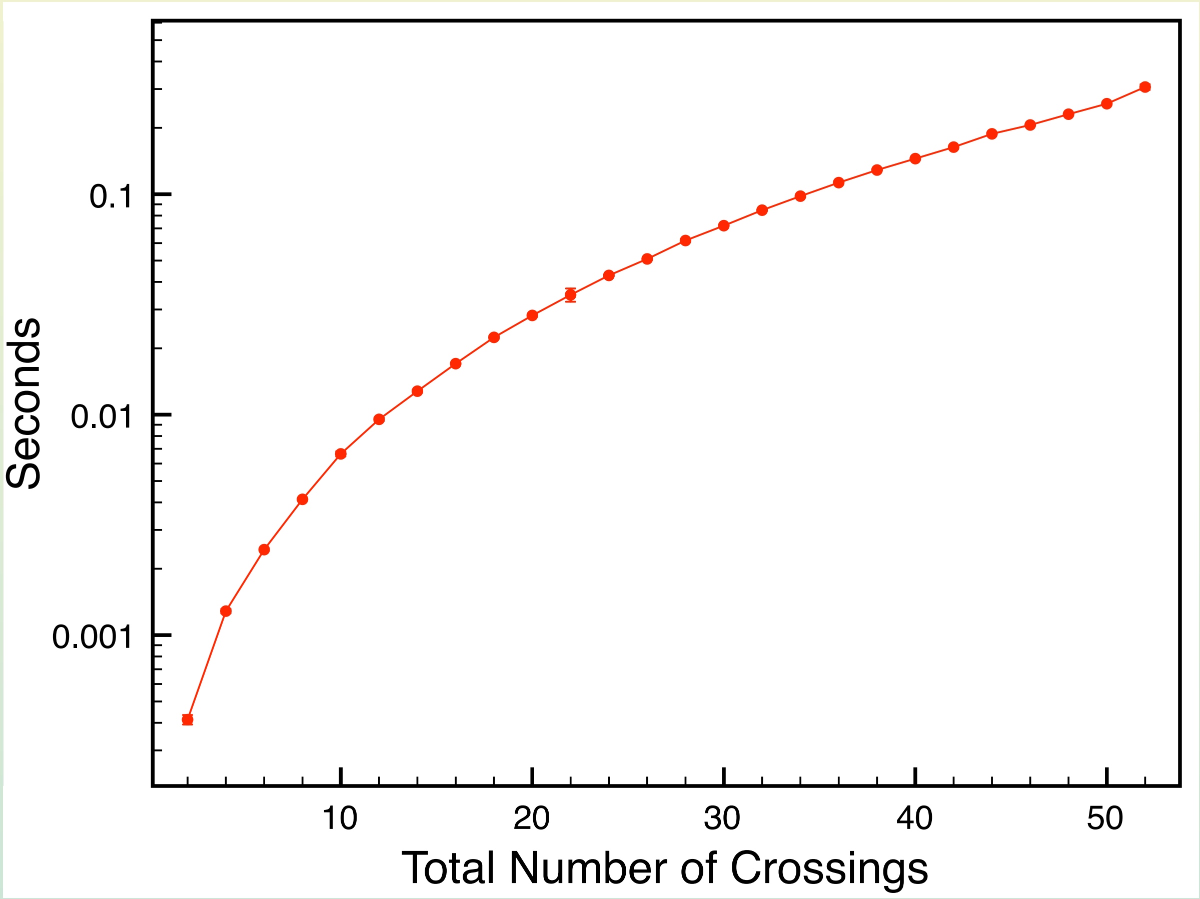
In this experiment there is only one CSEC.

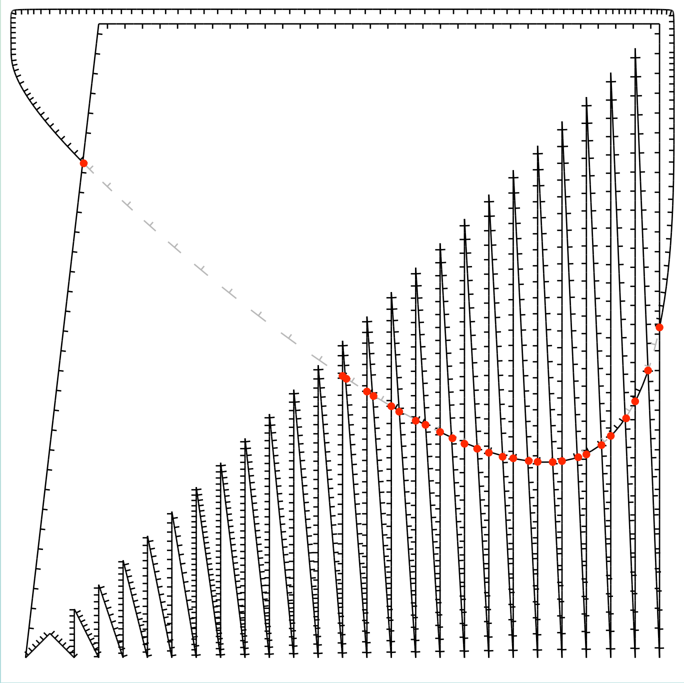
Finding CSECs on Labeled Figures

Running Time vs. # Crossings



Running Time vs. # Crossings
(log Y axis)



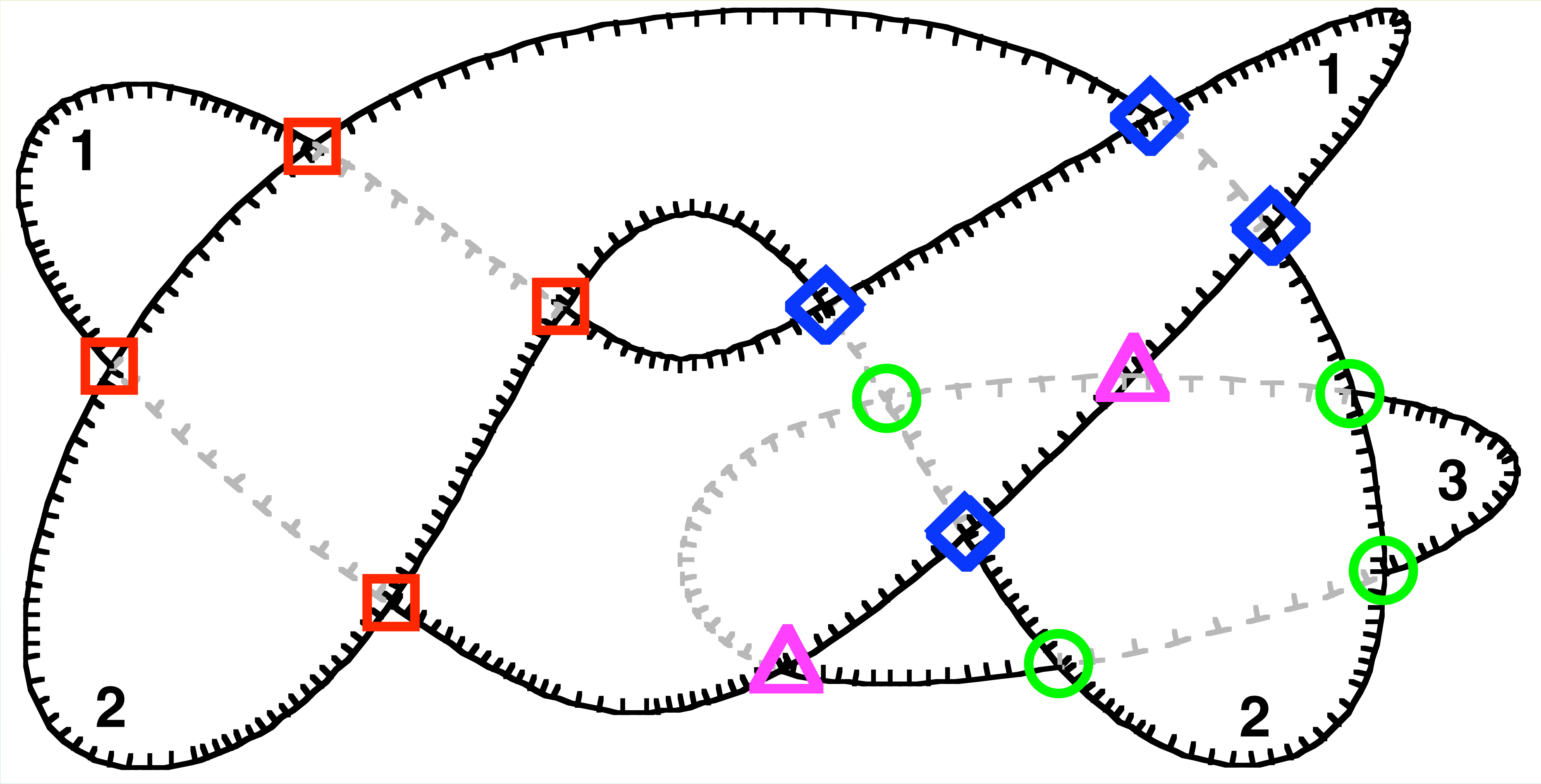


Running time to find CSECs for these figures is polynomial in the number of crossings.

Note: The actual time is very low (.3 secs for 52 crossings)

Crossing-State Equivalence Class Rule

All members of a crossing-state equivalence class must be in the same state.



e.g., for surfaces *2* and *3* all corners of the green circle CSEC must be in the same state, *i.e.*, either *2* is above *3 or vs/va*.

Two Relabeling Methods

1. *Druid (OLD)*: Performs a tree search (Wiley and Williams '06a).

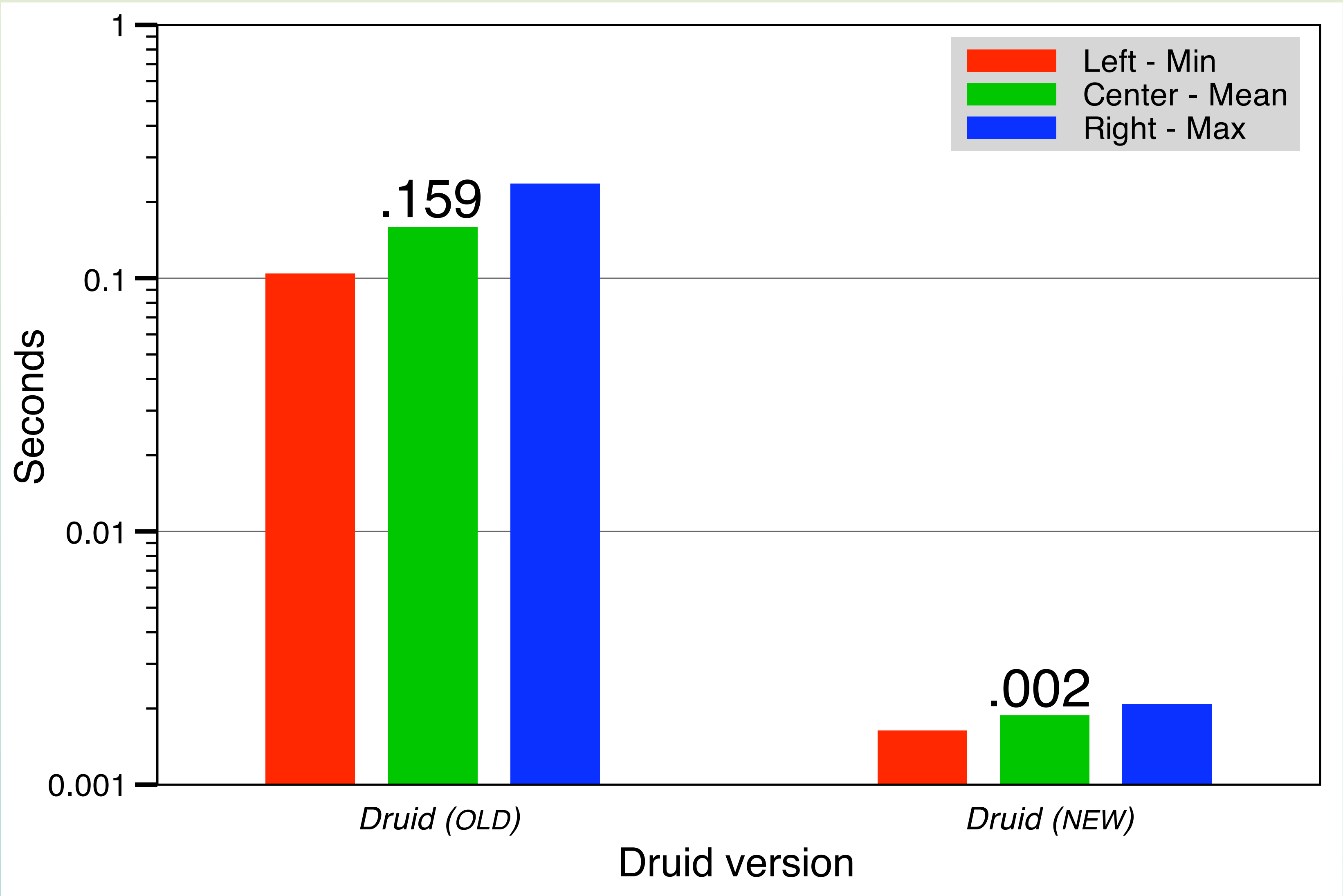
2. *Druid (NEW)*: Maintains the CSECs without a search. Deduces resulting segment depth changes directly (Wiley and Williams '06b).

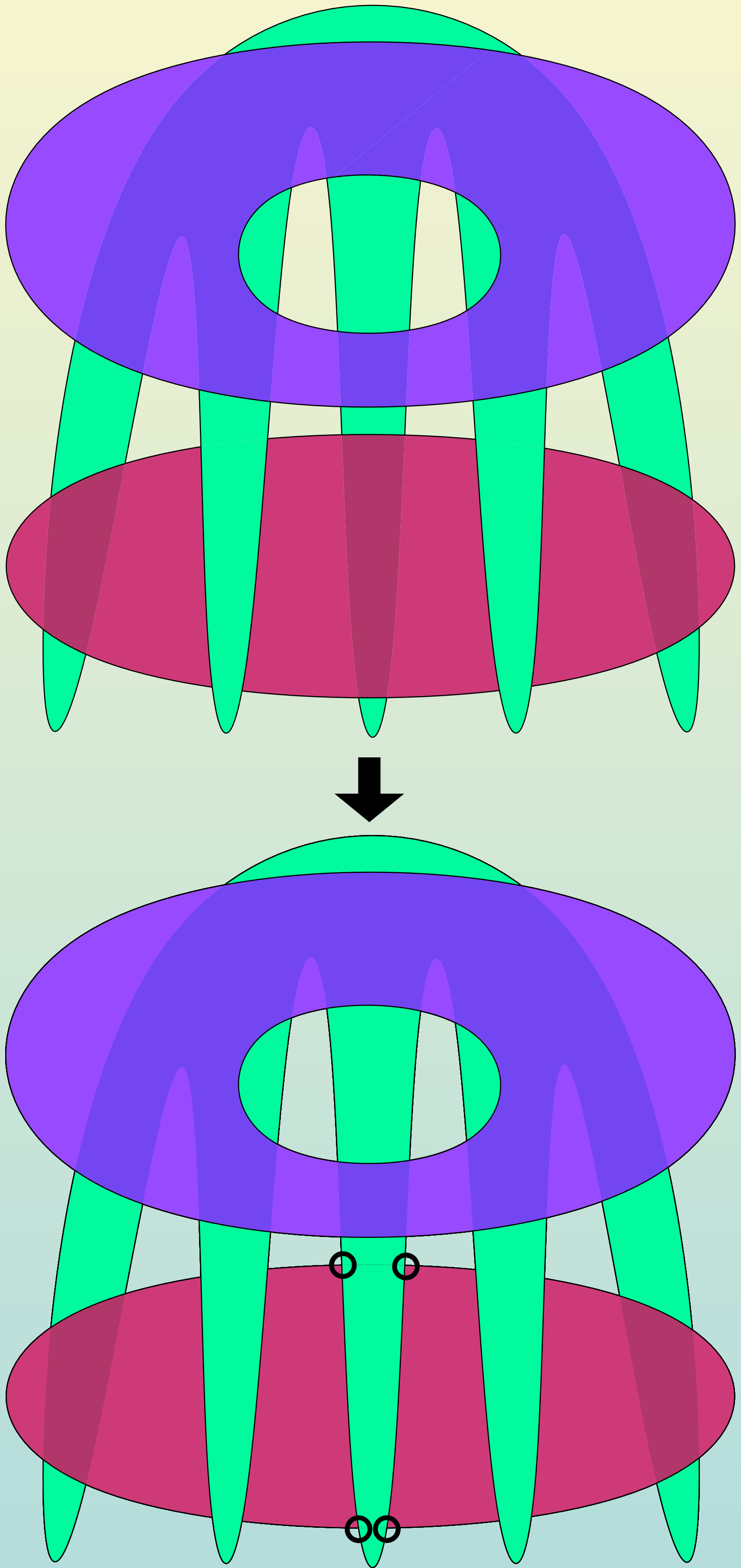
Wiley, K. B., and L. R. Williams, 2006. Representation of Interwoven Surfaces in 2 1/2 D Drawing. *Proc. of CHI*, Conference on Human Factors in Computing Systems, Montreal, Canada, 2006.

Wiley, K. B., and L. R. Williams. Use of Crossing-State Equivalence Classes for Rapid Relabeling of Knot-Diagrams Representing 2 1/2 D Scenes. Tech Report, UNM, Dept of Computer Science, TR-CS-2006-08, 2006.

Results: A Small CSEC Flip

- Size 4, indicated with circles
- Running times on 1.6GHz G5 PowerMac
- *Druid* (NEW) performs 85 times faster than *Druid* (OLD)

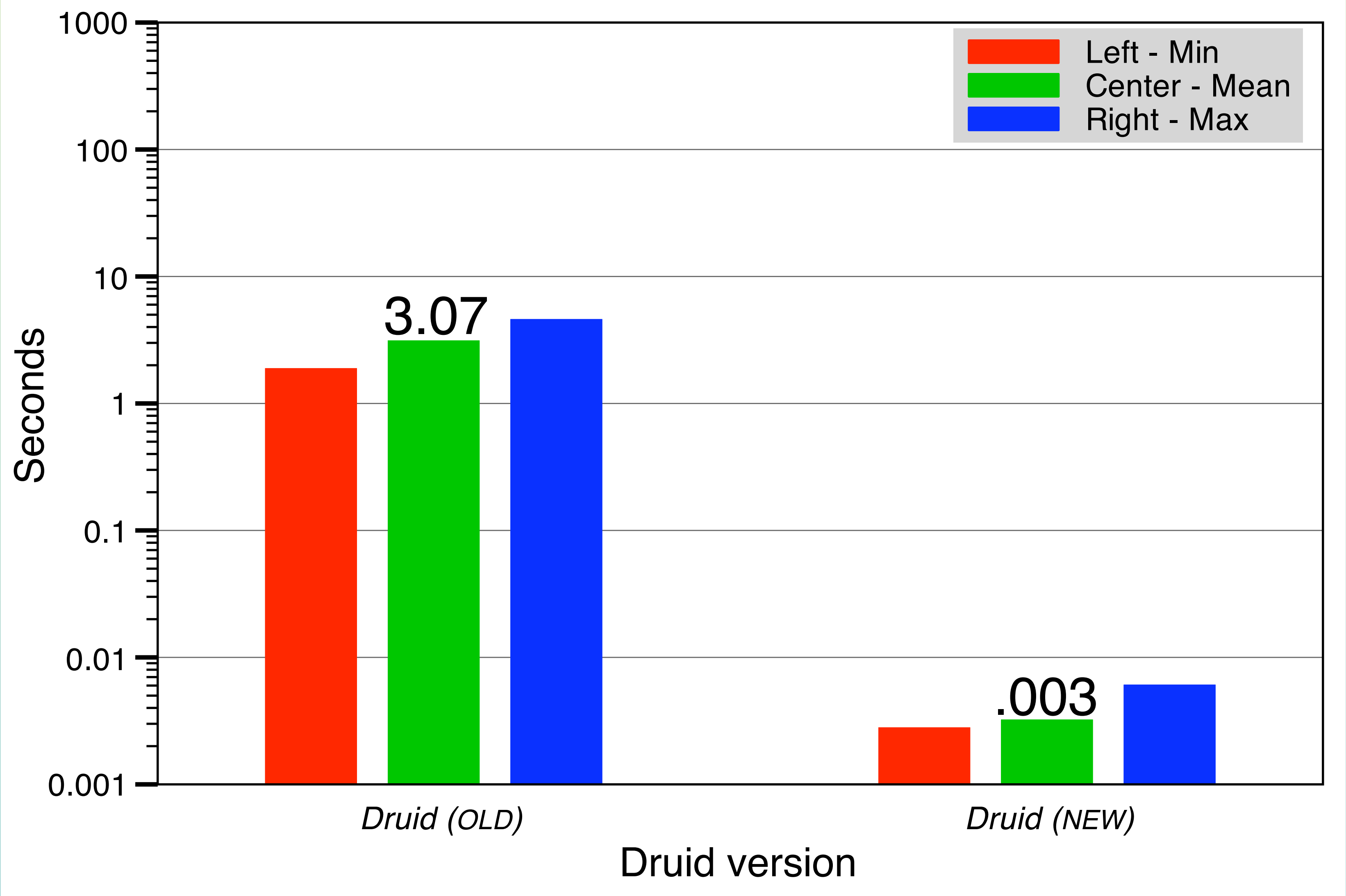


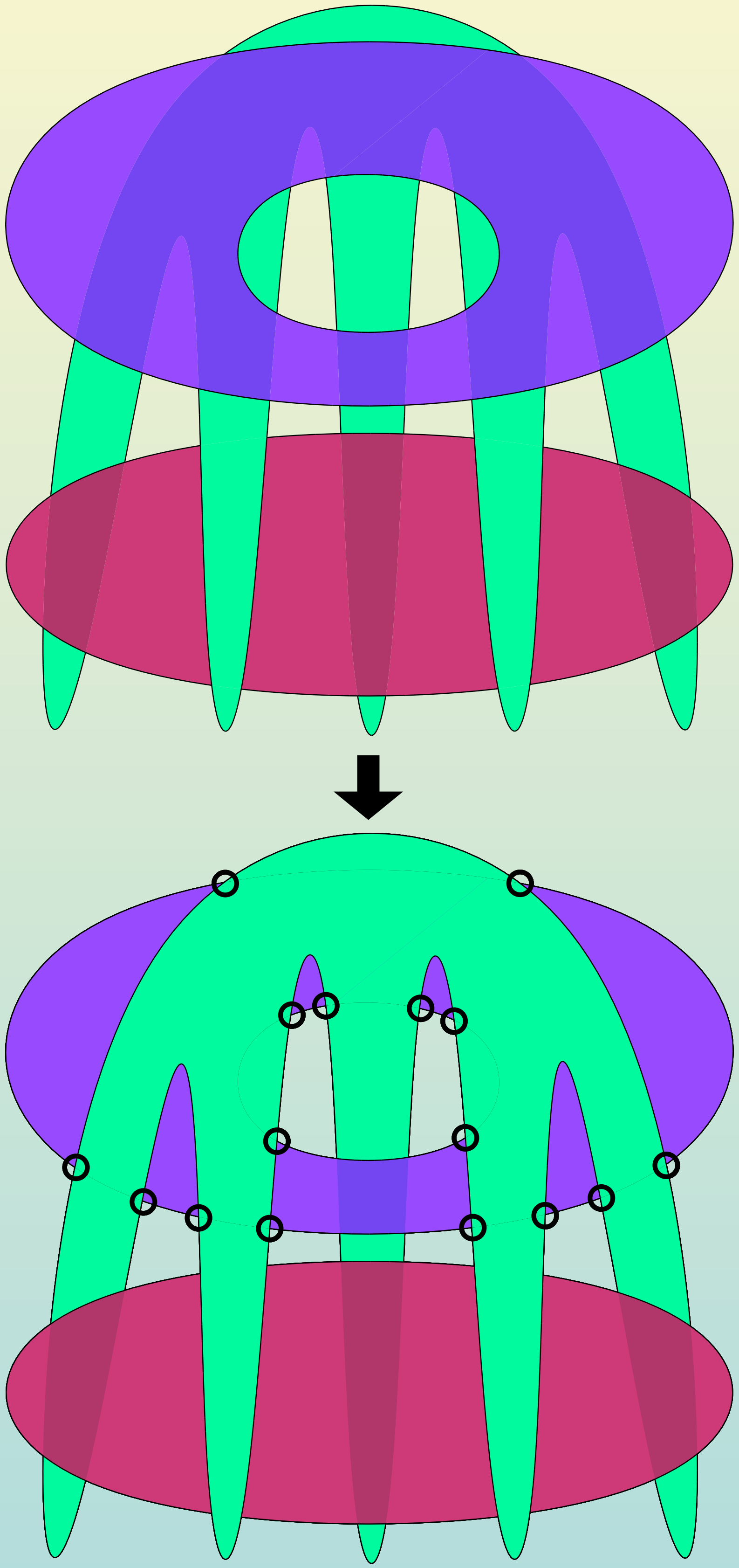


Min, mean, max with respect to a crossing-flip performed independently on each corner

Results: A Large CSEC Flip

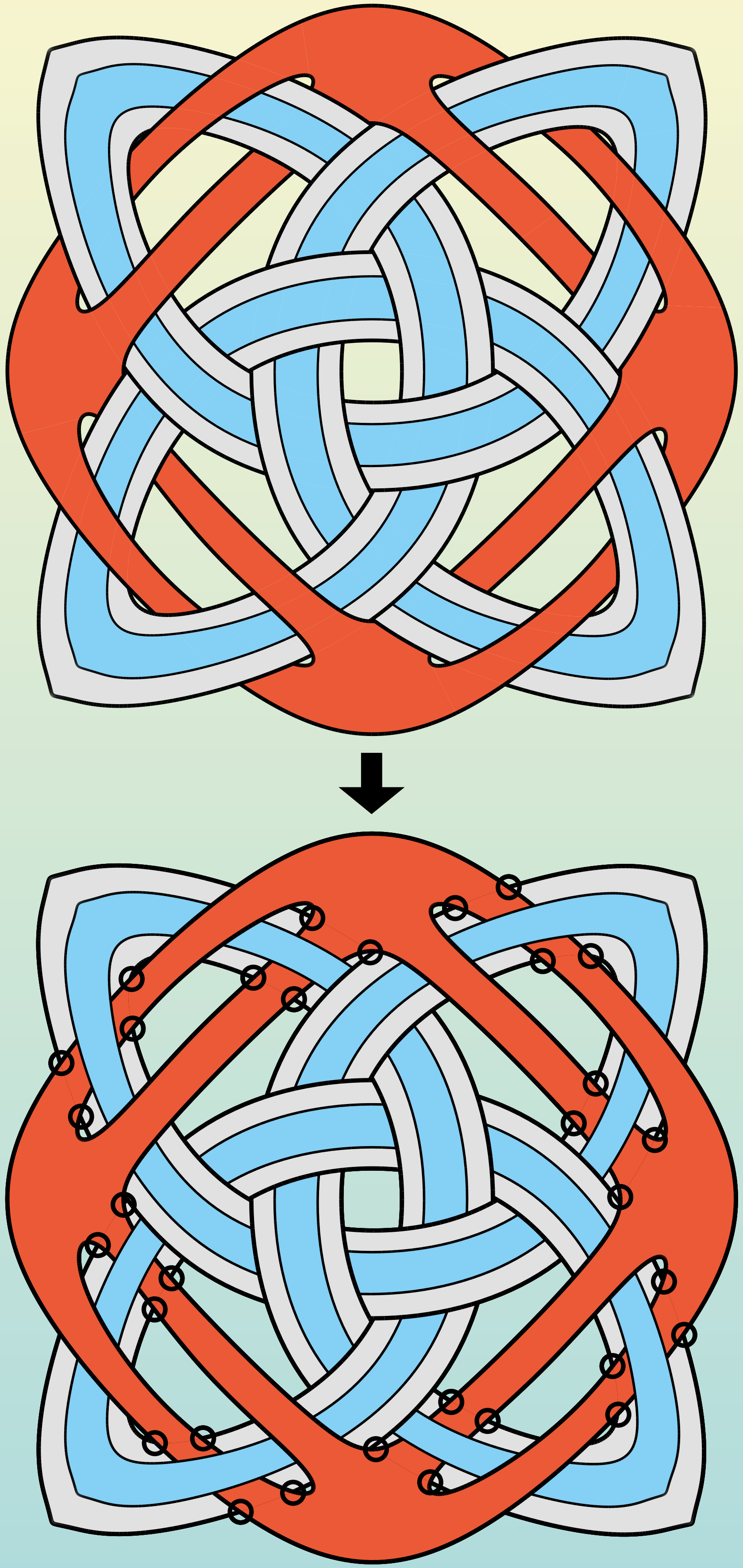
- Size 16, indicated with circles
- *Druid* (OLD) cannot relabel in a reasonable time
- *Druid* (NEW) performs 967 times faster
- Note: *Druid* (OLD) failed 50% of the time



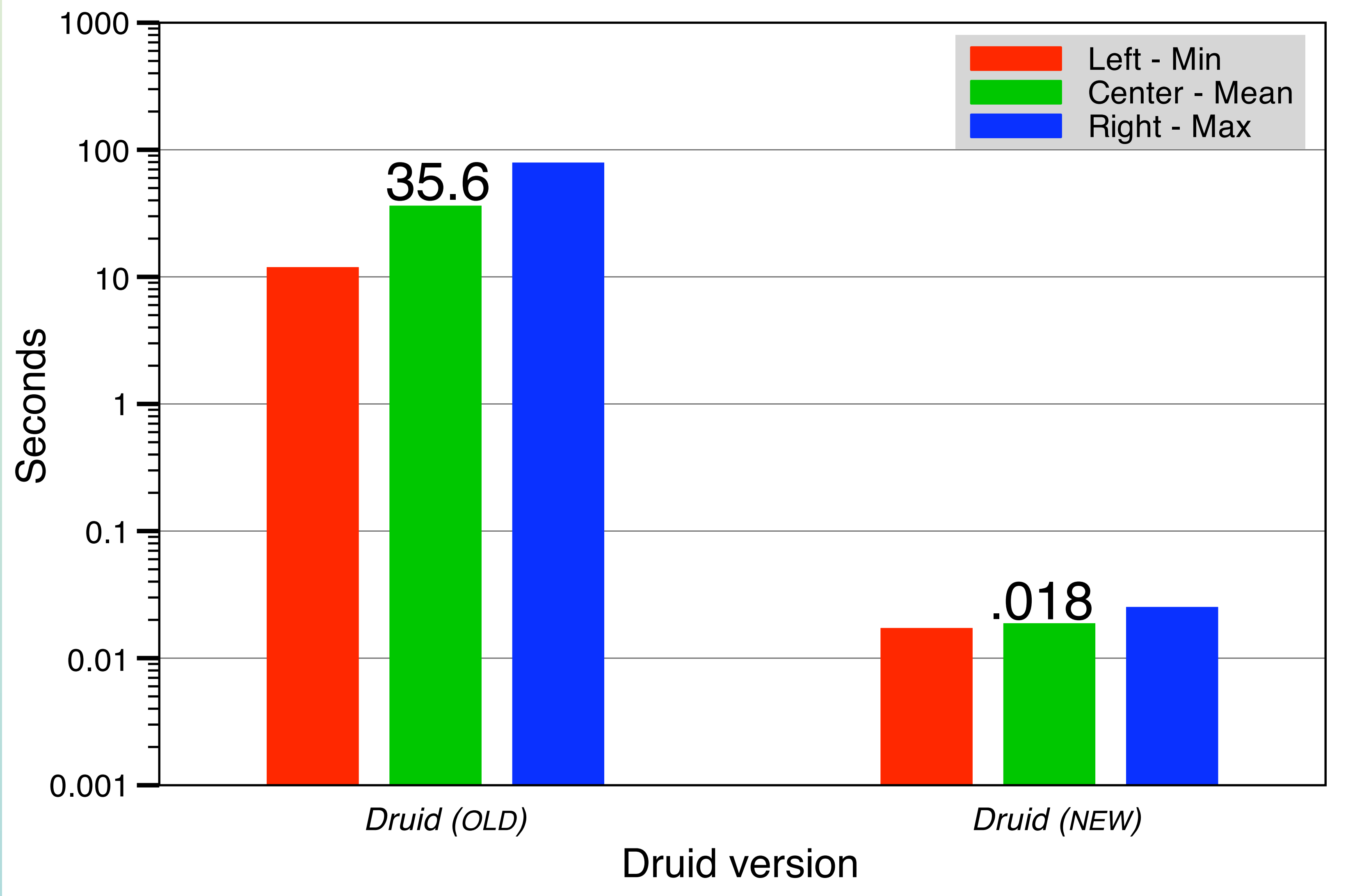


Min, mean, max with respect to a crossing-flip performed independently on each corner

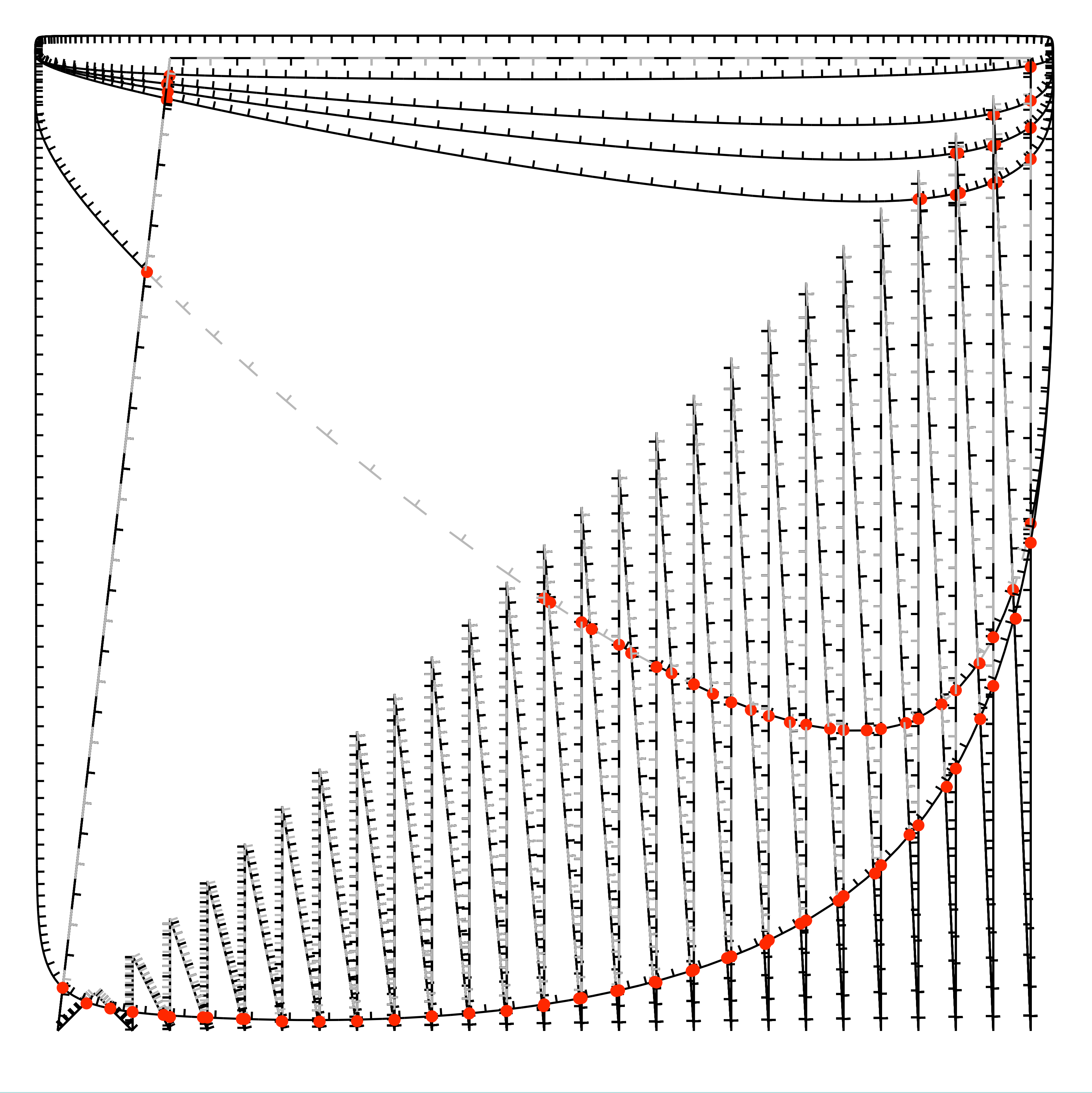
Results: A Complex Figure



- 256 crossings, 64 CSECs
- *Druid* (OLD) cannot relabel this small CSEC flip in a reasonable time
- *Druid* (NEW) relabels in .02 seconds, 1900 times faster
- Note: *Druid* (OLD) failed 2% of the time



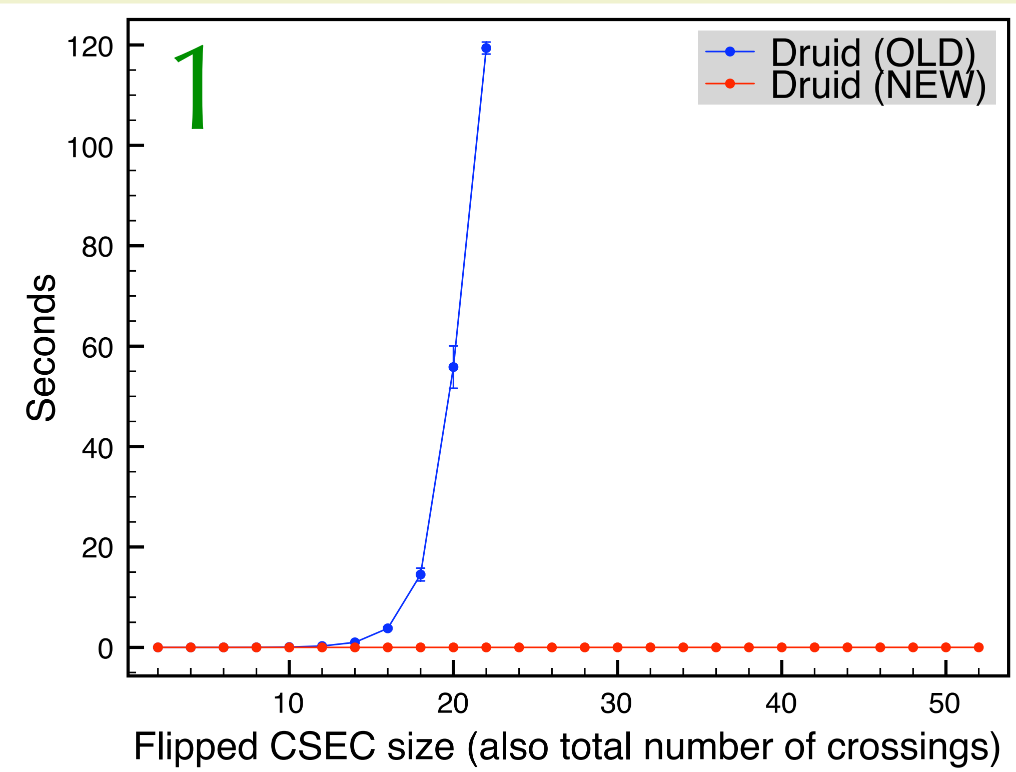
CSEC Flip Performance

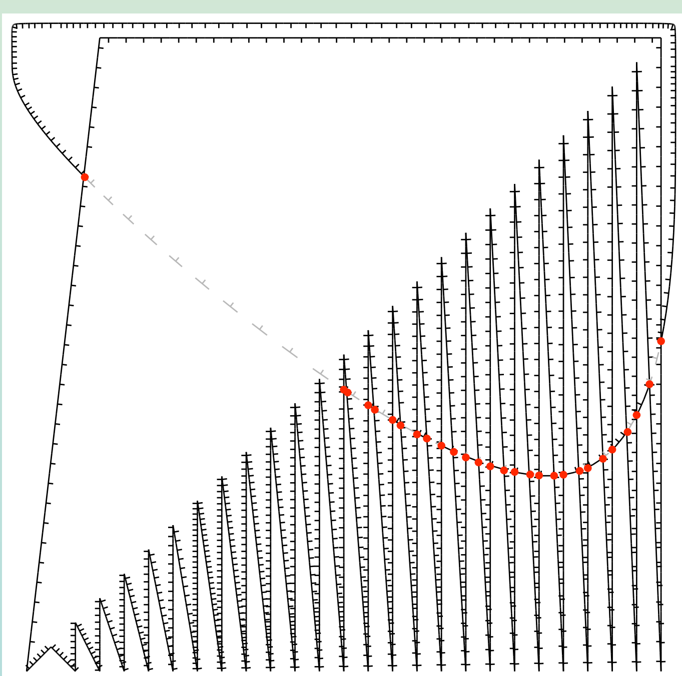


Flipped CSEC size: linear in the total number of crossings

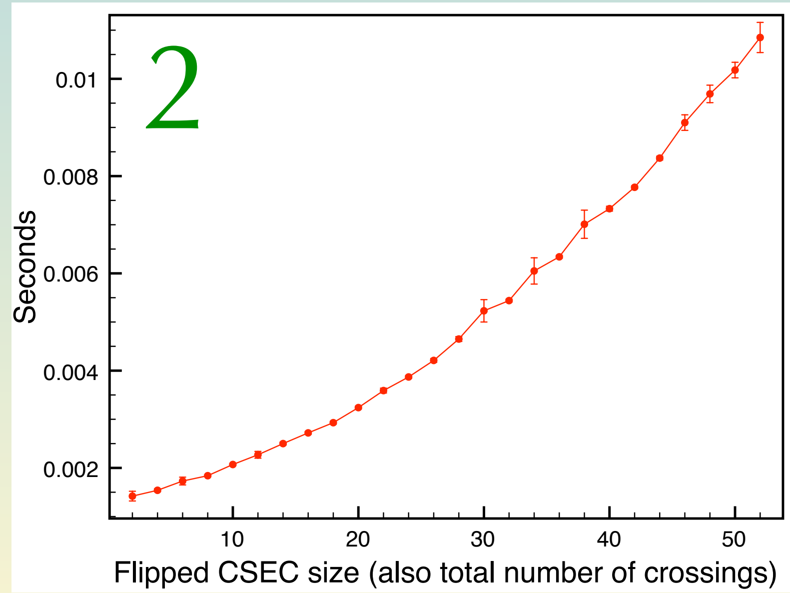
CSEC Flip Performance

Running time vs. CSEC size

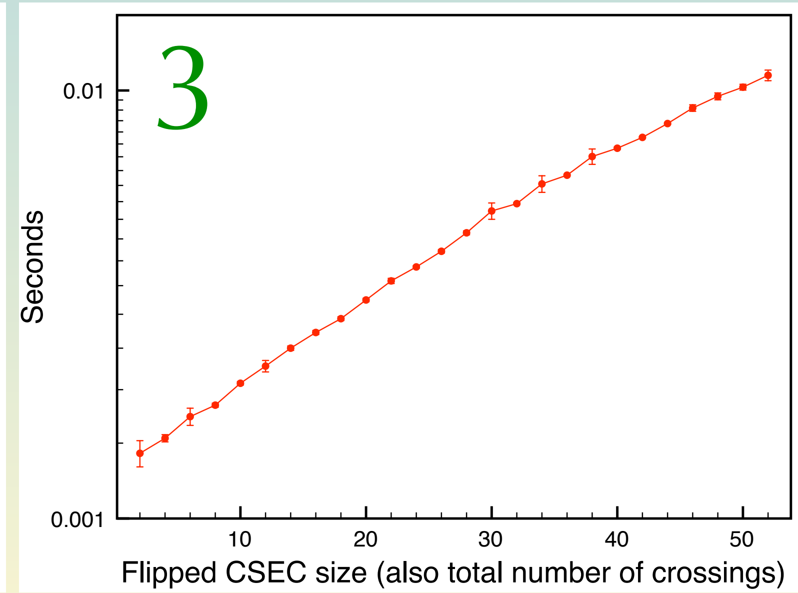




CSEC Flip Performance (*Druid* (NEW))

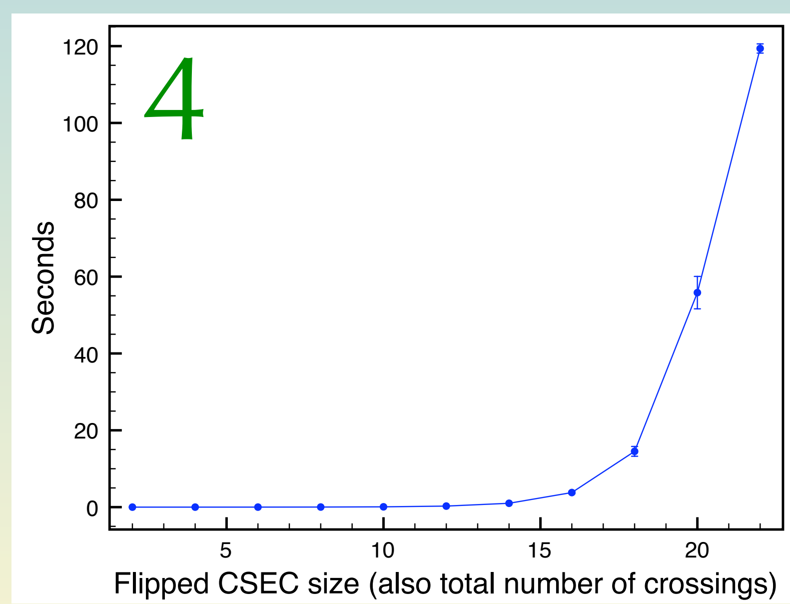


CSEC Flip Performance (*Druid* (NEW))
(log Y axis)

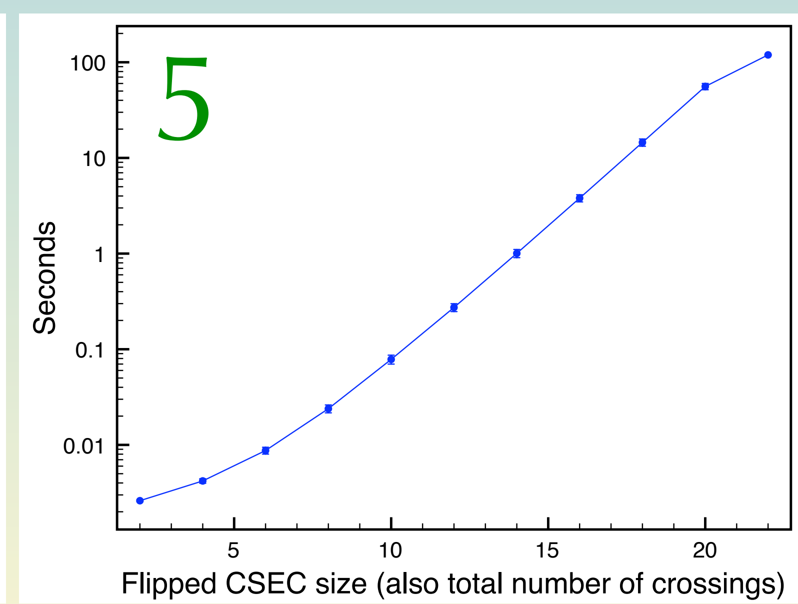


Performance is polynomial w.r.t. CSEC size

Search Performance (*Druid* (OLD))



Search Performance (*Druid* (OLD))
(log Y axis)



Performance is exponential w.r.t. CSEC size

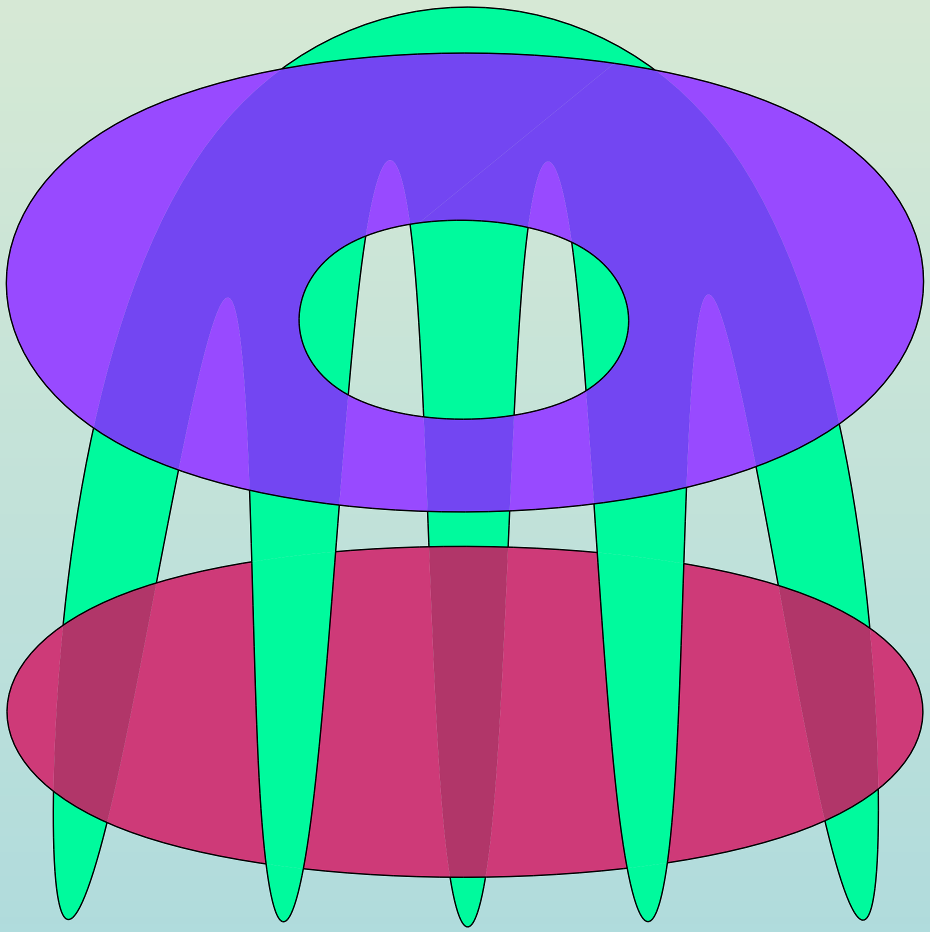
To CSEC flip test 2

Future Work

- Labeling with CSECs
- ***Locking*** and ***kinematic*** interactions
- ***Occluding contours*** and ***pita surfaces***

Future Work: Labeling with CSECs

- CSECs have a profound effect on the search space size
- e.g., this drawing has 40 crossings but only 7 CSECs, an improvement by a factor of 2^{33}, or 8.5 billion

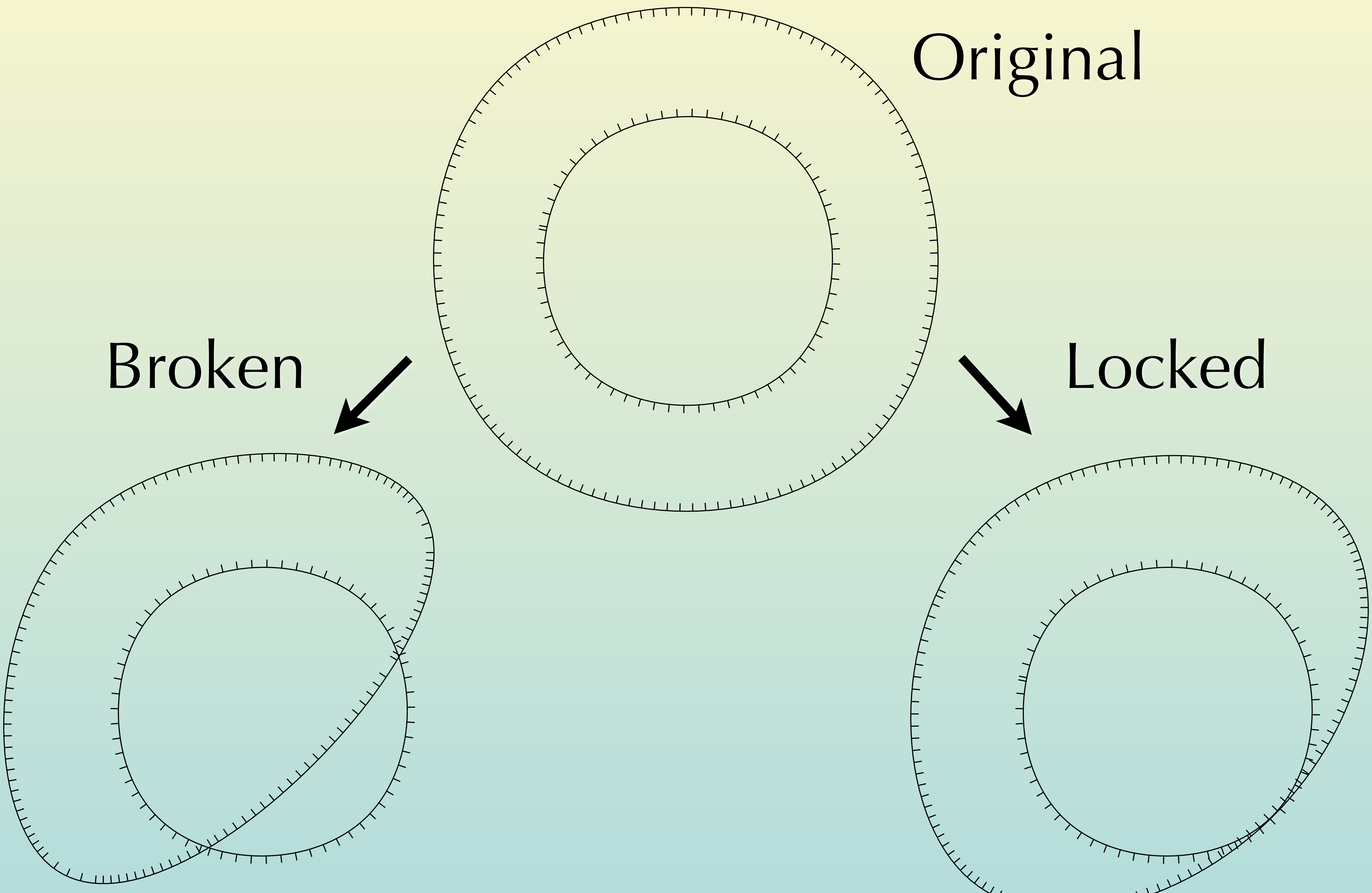


CSECs Used	Crossing-state search space size
No	2^{40} (for 40 crossings)
Yes	2^{7} (for 7 CSECs)

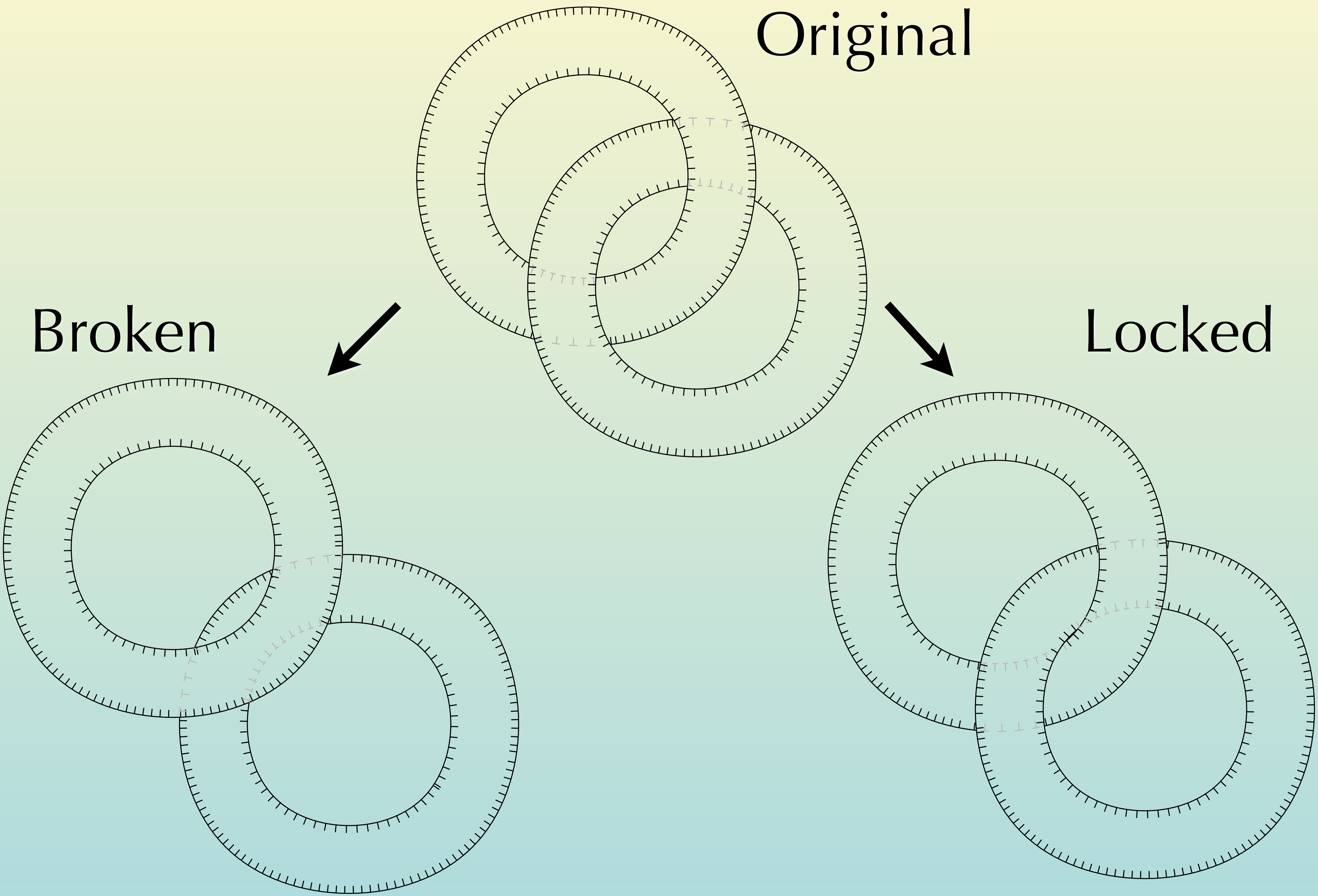
Labeling with CSECs

- Currently, can only find CSECs on legally labeled figures
- Cannot use CSECs to ***label***, only to ***relabel***
- Labeling must search the naive search space 2^C, not the improved search space 2^E
- Having the CSECs for an unlabeled figure would greatly assist the labeling search

Future Work: Locking Interactions

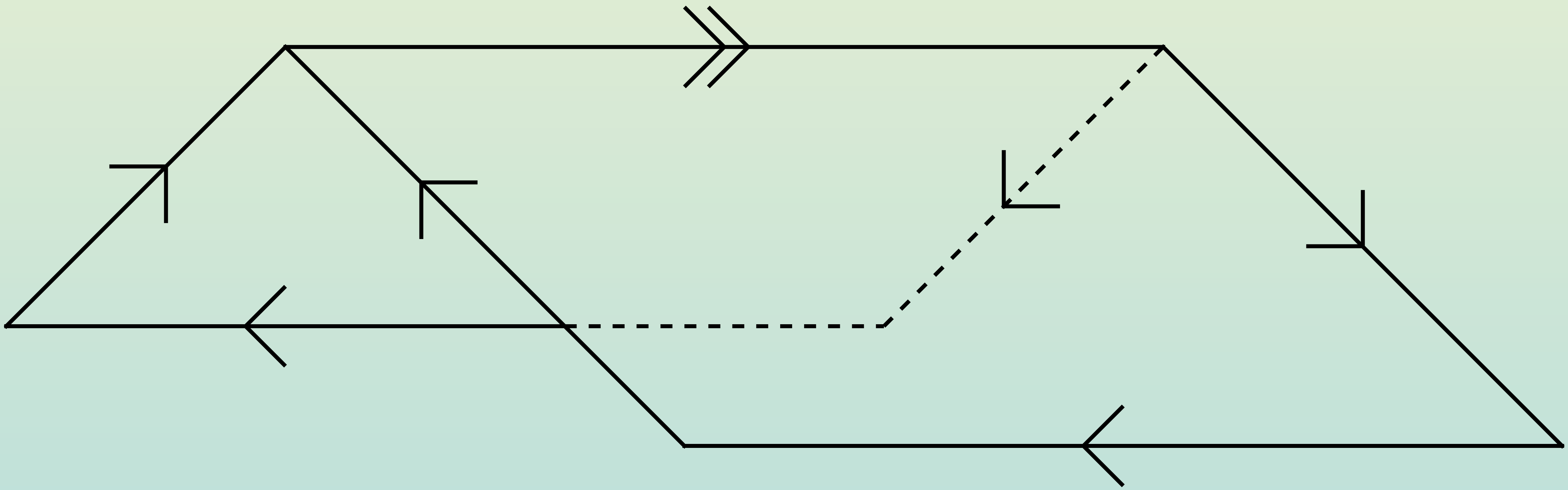


Locking and Kinematic Interactions



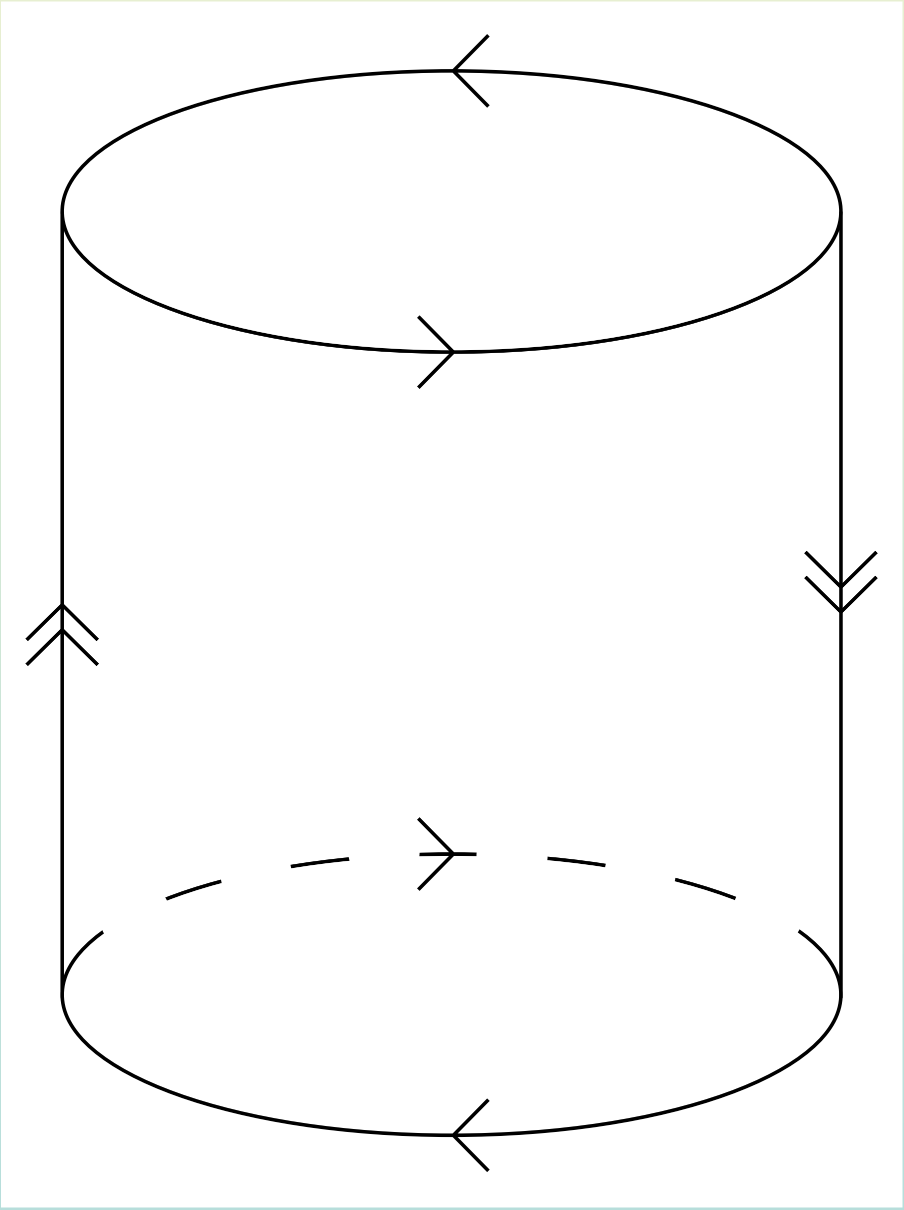
Future Work: Occluding Contours and Pita Surfaces

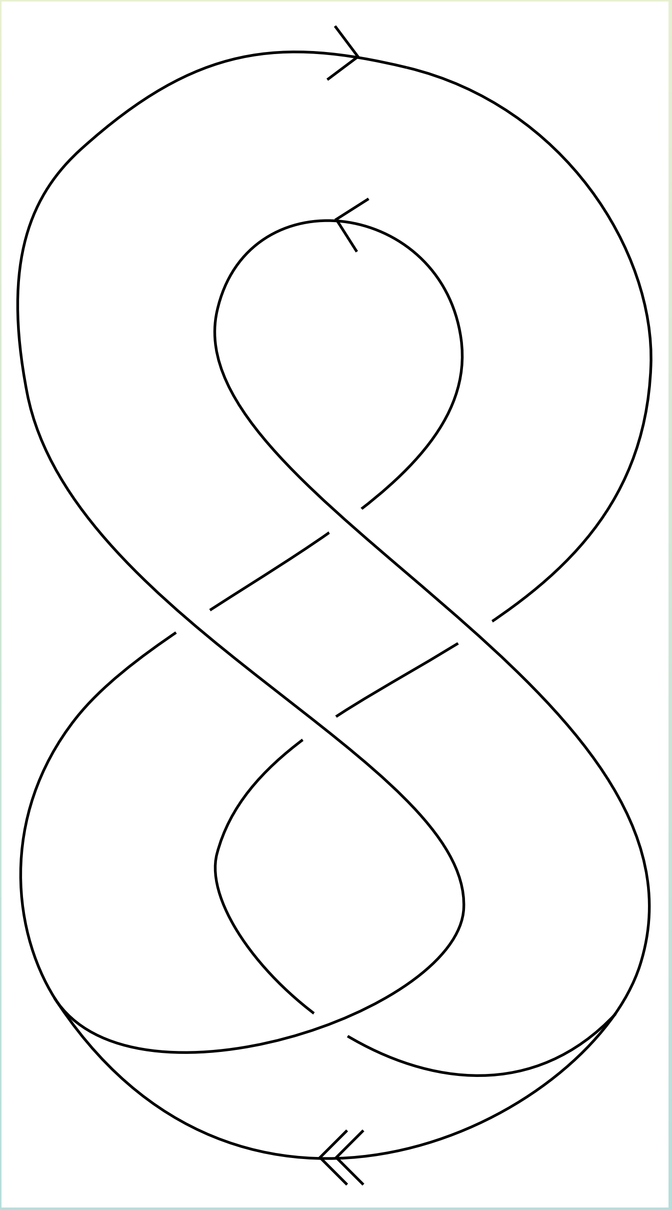
An ***occluding contour*** is the projection of a fold.



Occluding Contours: Examples

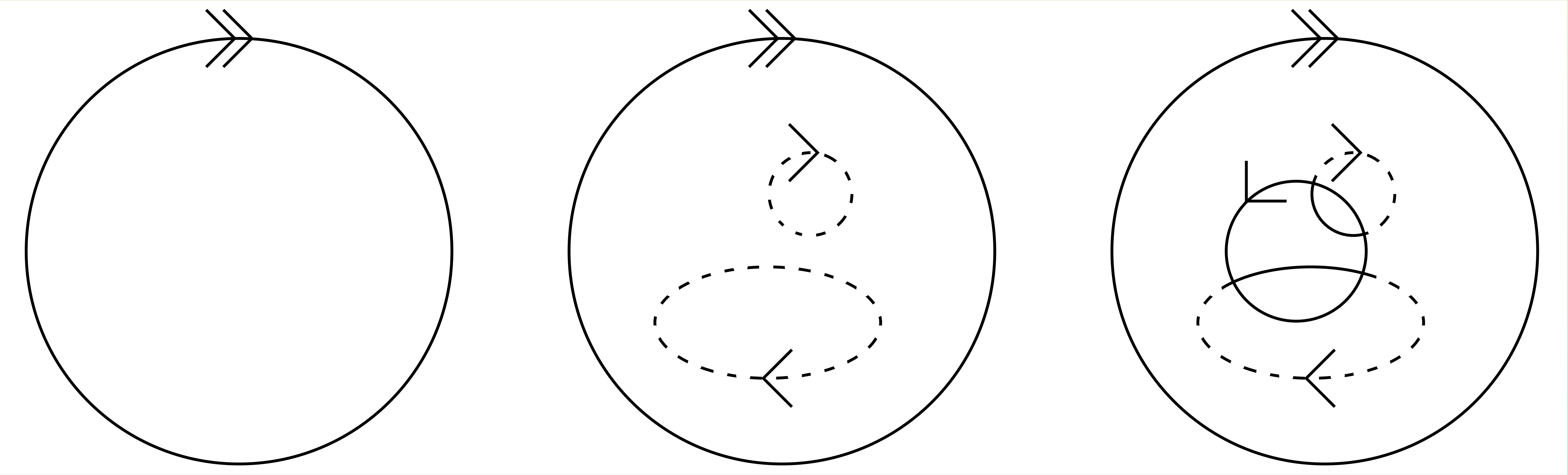
Occluding contours enable construction of cylinders and Mobius strips.





Occluding Contours: Pita Surfaces

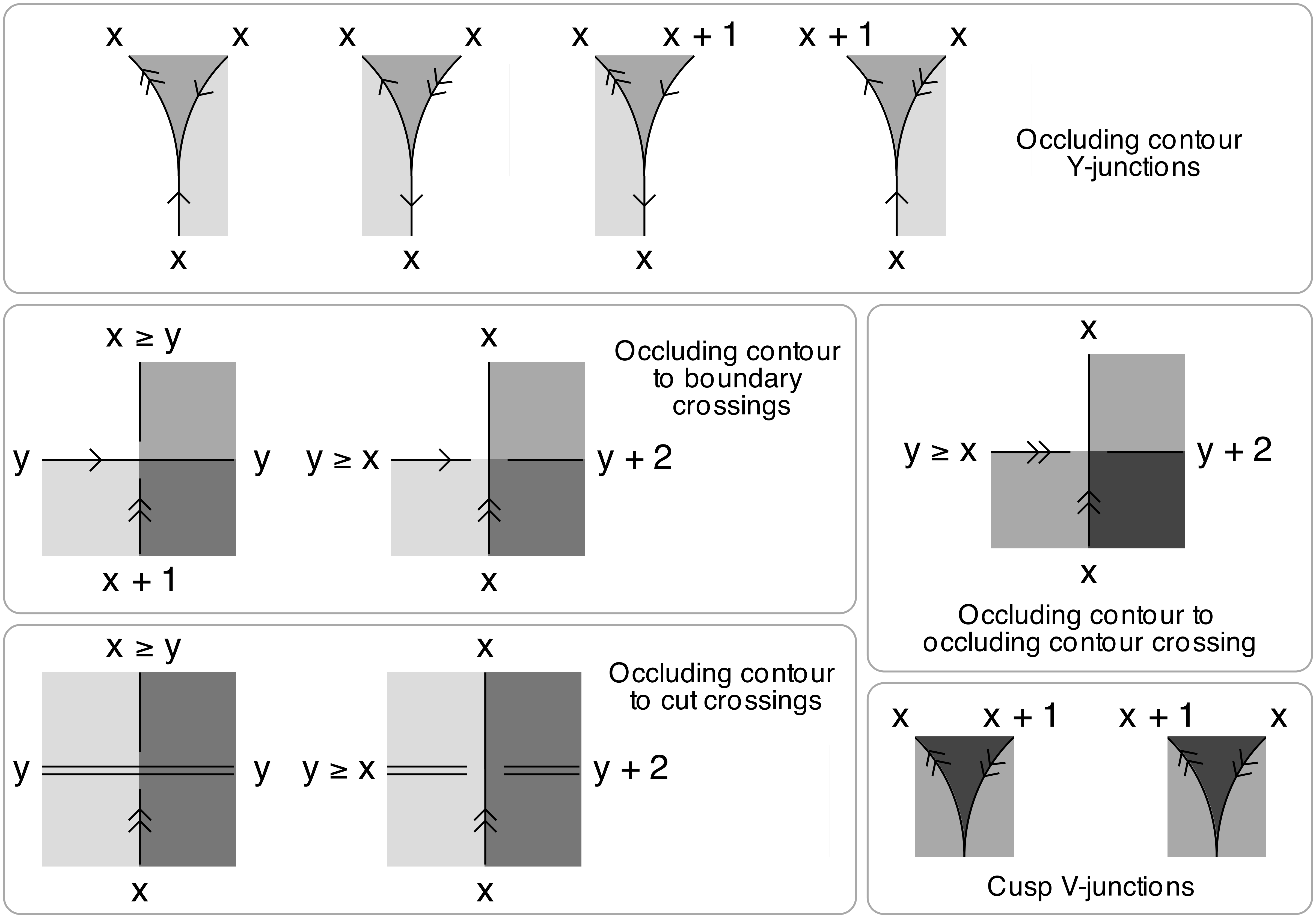
Occluding contours enable construction of ***pita*** surfaces.



pita surface

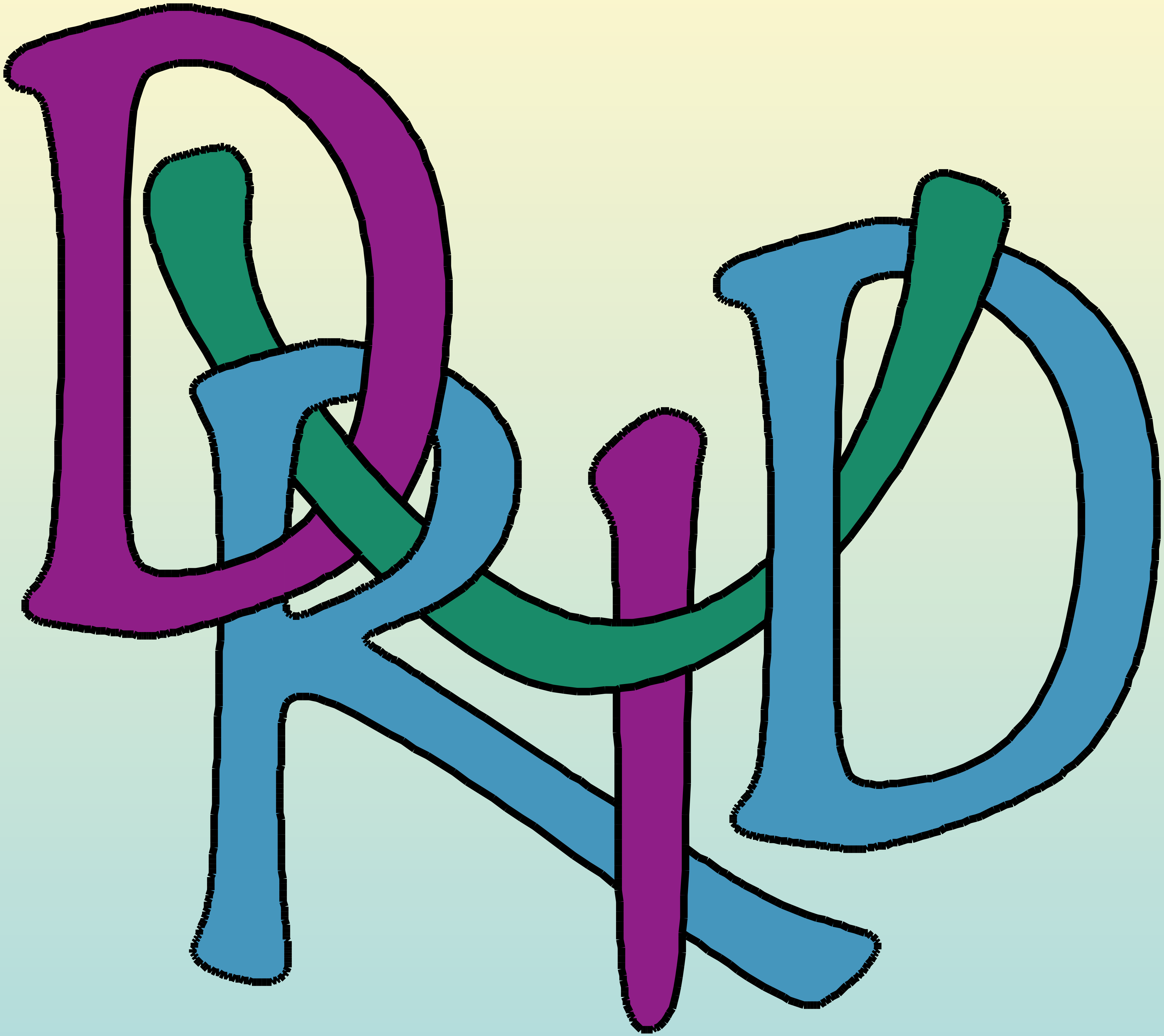
pita ***containment***

Occluding Contour Labeling Schemes

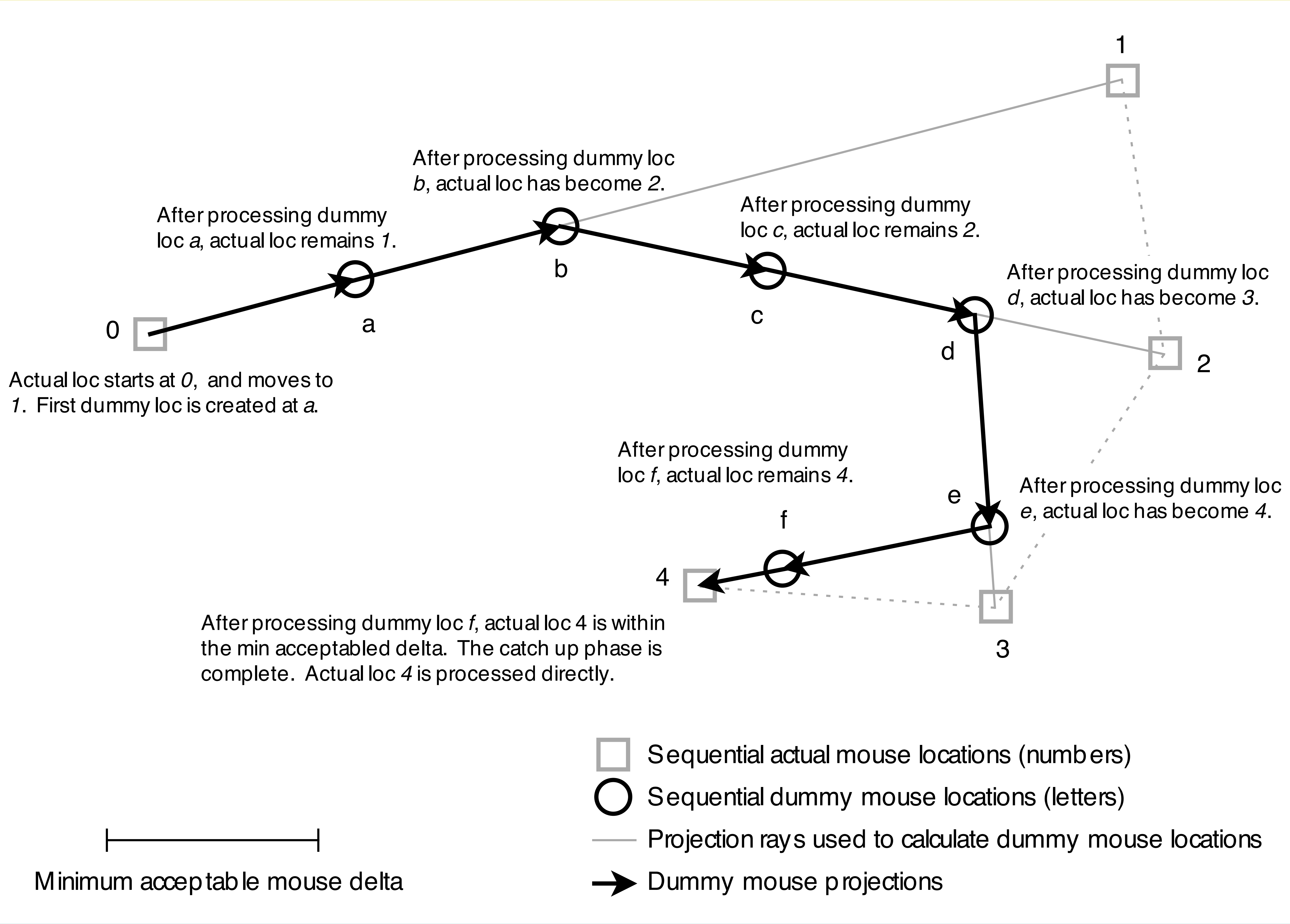


Conclusions

- Developed *Druid*, a system for constructing interwoven 2½D scenes
- Use of branch-and-bound search to relabel gives the user the experience of interacting directly with idealized physical surfaces
- Search hinders *Druid's* scalability
- Discovered a topological property of 2½D scenes, the crossing-state equivalence class rule
- Exploitation of this property can alleviate the need to search in some situations, and can dramatically reduce the search space in remaining situations
- Vastly extended the complexity of drawings that users of *Druid* can construct



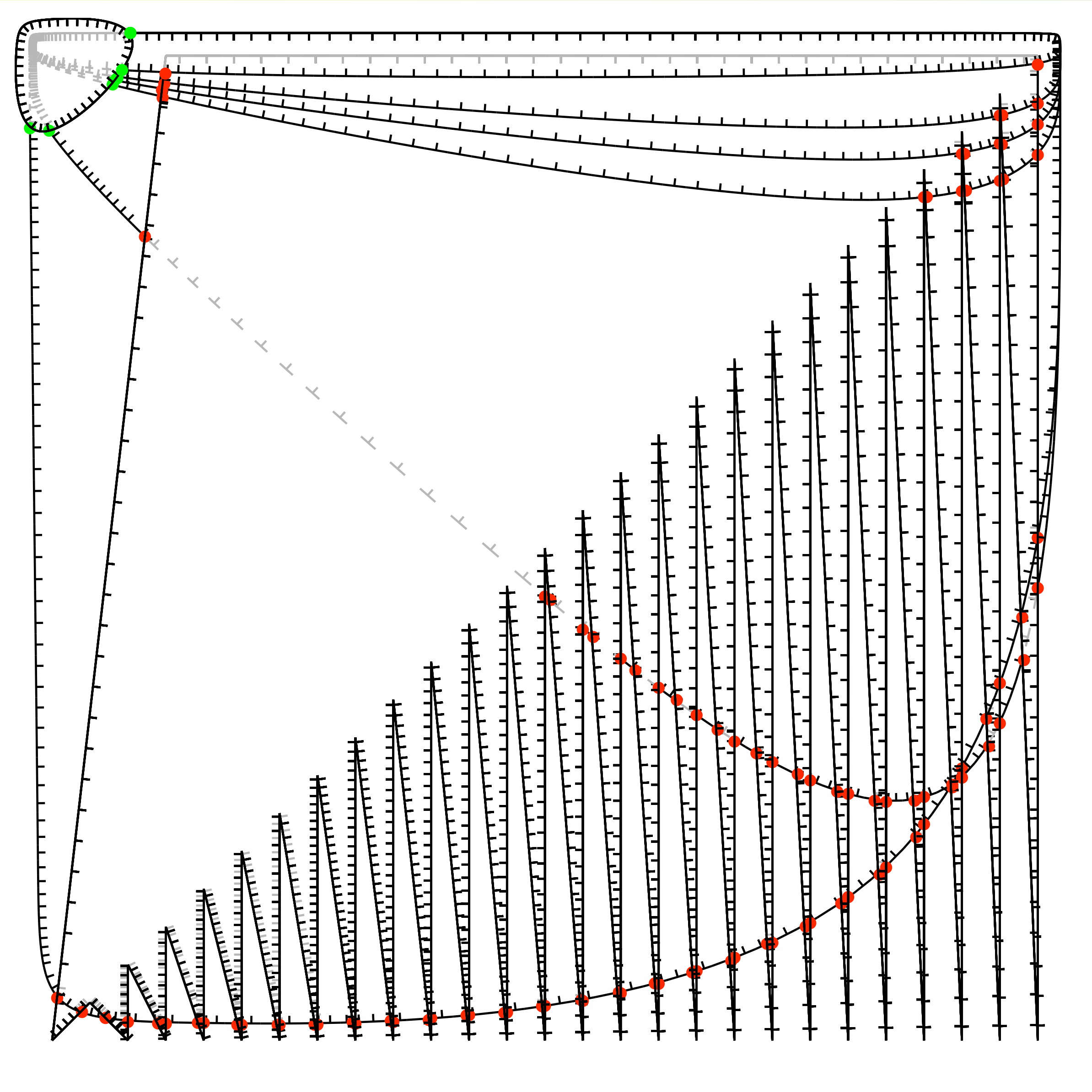
Min. Acceptable Mouse Delta



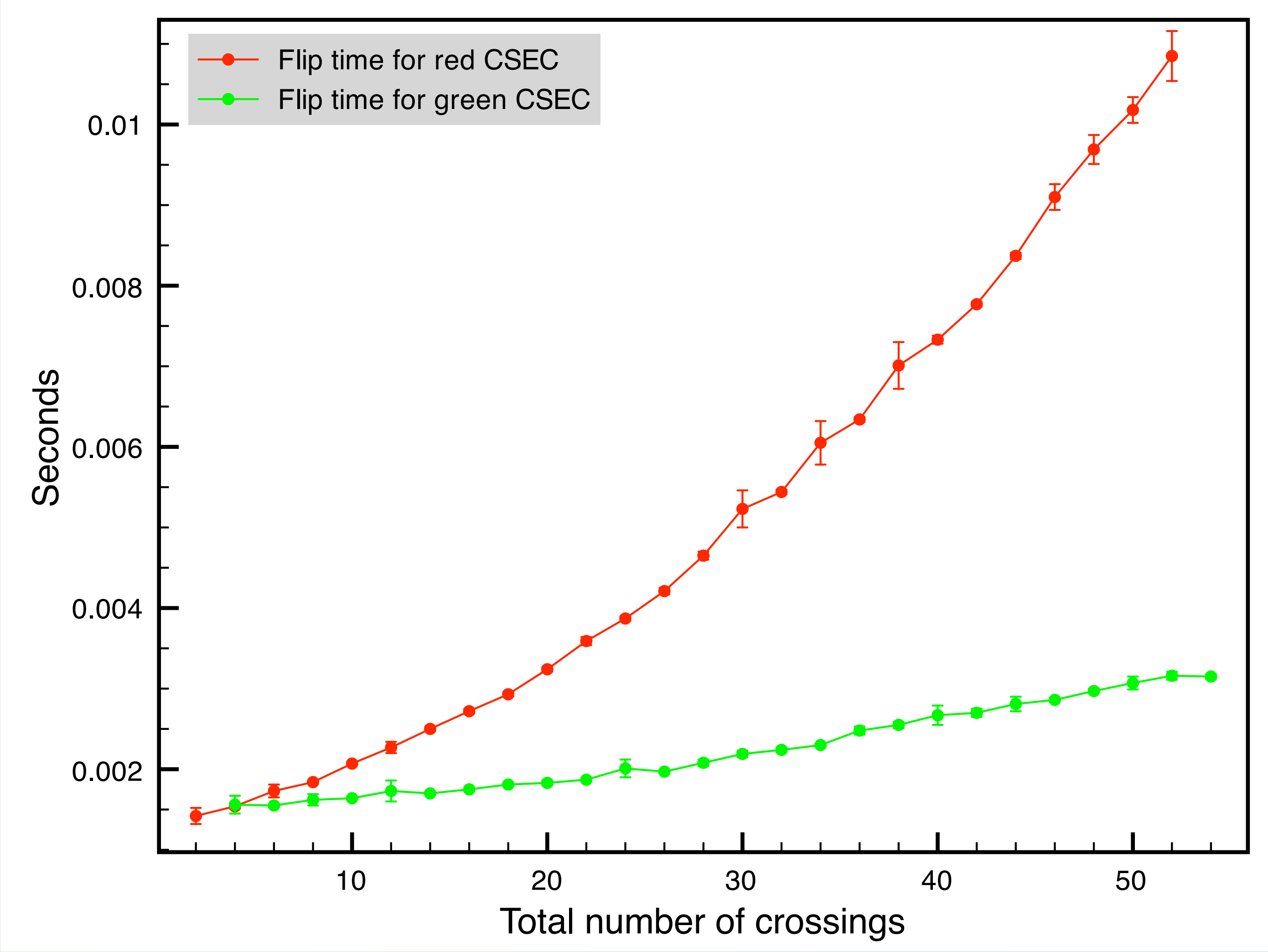
Back

CSEC Flip Performance

Flipped CSEC size:
constant (green)



Running time vs.
Total Number of Crossings



Red plot is the same plot shown on the previous slide
(seconds to perform the red CSEC flip)

Back to CSEC flip test 1

Depth Sort vs. *Druid*

- ***Depth Sort:***
  - Uses cuts to remove cycles and create a DAG.
  - Renders by sorting polygons in 3D from back to front.
- ***Druid*:**
  - Uses cuts to group boundaries **not** to remove cycles.
  - Makes weaker assumptions to render than required by depth sort – does not require DAG.

[1] Angel, E. *Interactive Computer Graphics*. Addison-Wesley, 2006.

[2] Foley, vanDam, Feiner, and Hughes. Computer Graphics, Principles and Practice. Addison-Wesley, 2000.

Scanline Algorithms vs. *Druid*

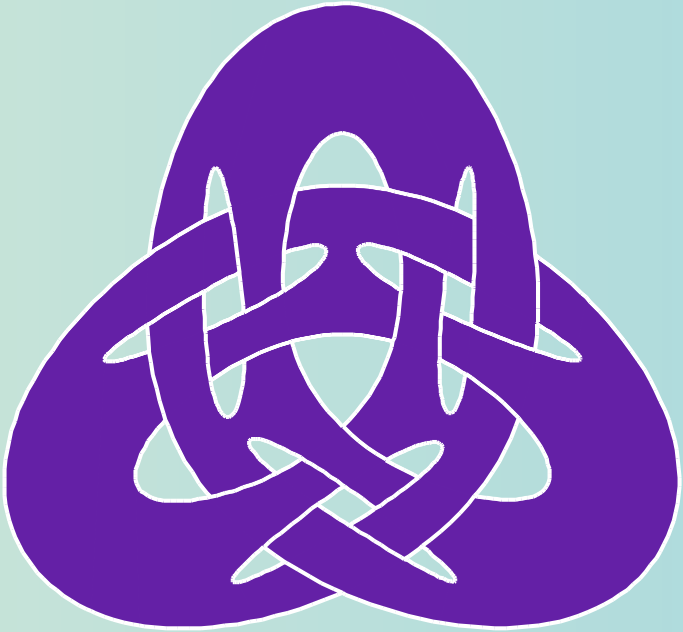
- ***Scanline algorithms***:
  - Raster-based
  - Method for rendering vector objects
- ***Druid:***
  - Vector-based
  - Relies on graphical API to render vector objects

[1] Barkan, E., and D. Gordon. The Scanline Principle: Efficient Conversion of Display Algorithms into Scanline Mode. *The Visual Computer*, **15**(249), 1999.

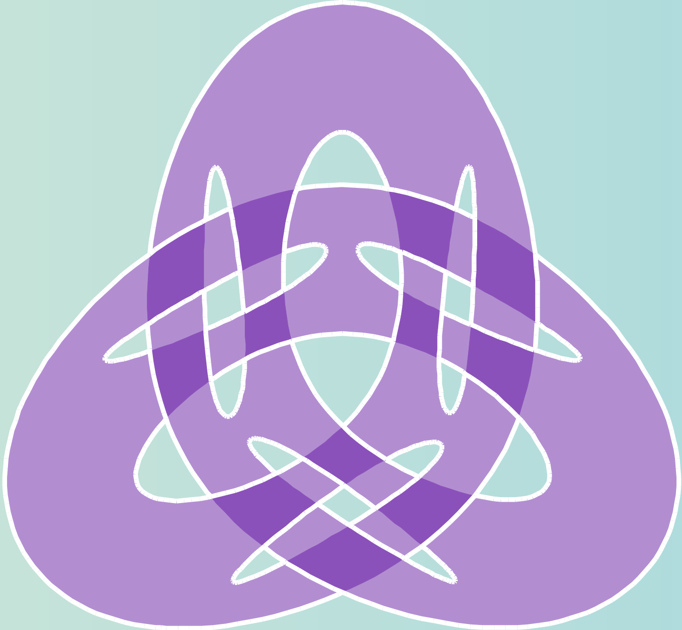
[2] http://www.devmaster.net/wiki/Scanline_algorithm

Hidden Surface Removal vs. *Druid*

- ***Hidden surface removal***:
  - Assumes opaque surfaces bounding solid objects



- ***Druid***:
  - Assumes transparent fronto-parallel surfaces
  - Opaque surfaces are a special case



[1] Weiler K. and Atherton P. Hidden Surface Removal Using Polygon Area Sorting. ACM SIGGRAPH Computer Graphics, *Proceedings of ACM SIGGRAPH 77*, **11**(3) pp. 214-222, 1977.

[2] Metelli, F., The perception of transparency, Scientific American, 230(4), pp. 90-98, 1974.