Druid:

Representation of Interwoven Surfaces in 2½D Drawing

Dr. Keith Wiley

Dr. Lance R. Williams

This work completed while at:
University of New Mexico
Department of Computer Science
Albuquerque, NM 87131 USA

Current location:
Applied Physics Laboratory
University of Washington
Seattle, WA 98105 USA

Druid:

Toward a New Dimension In Vector Drawing

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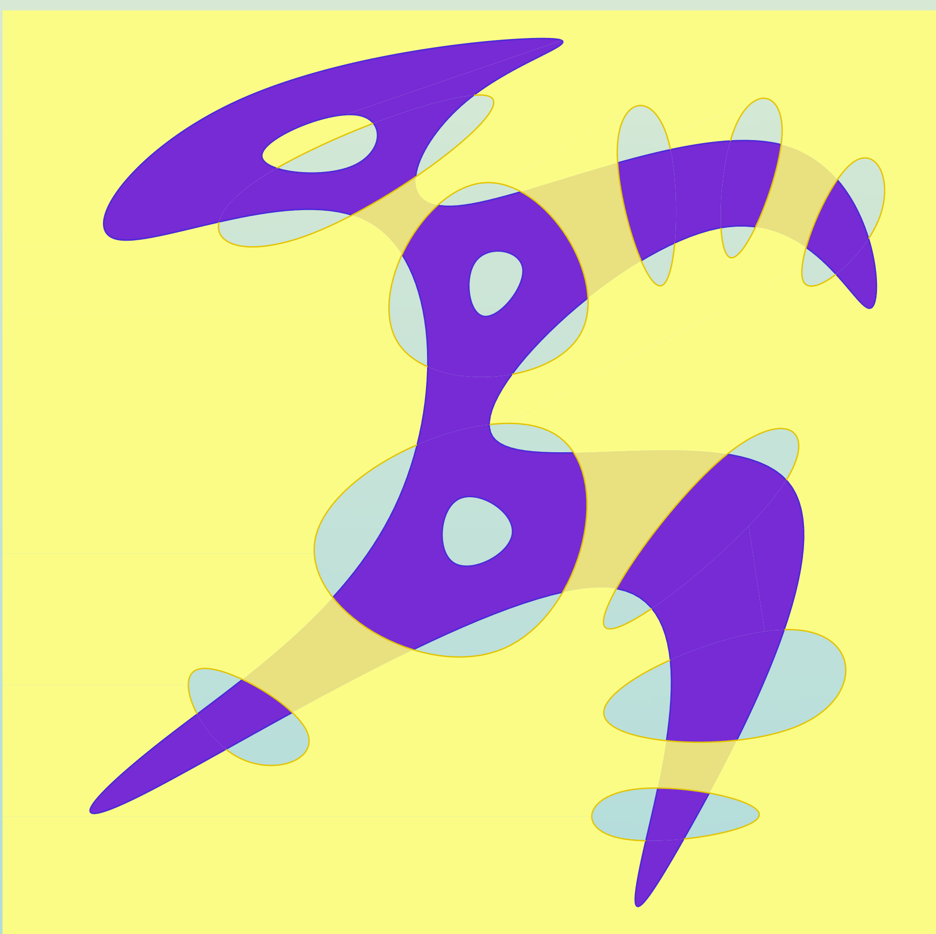
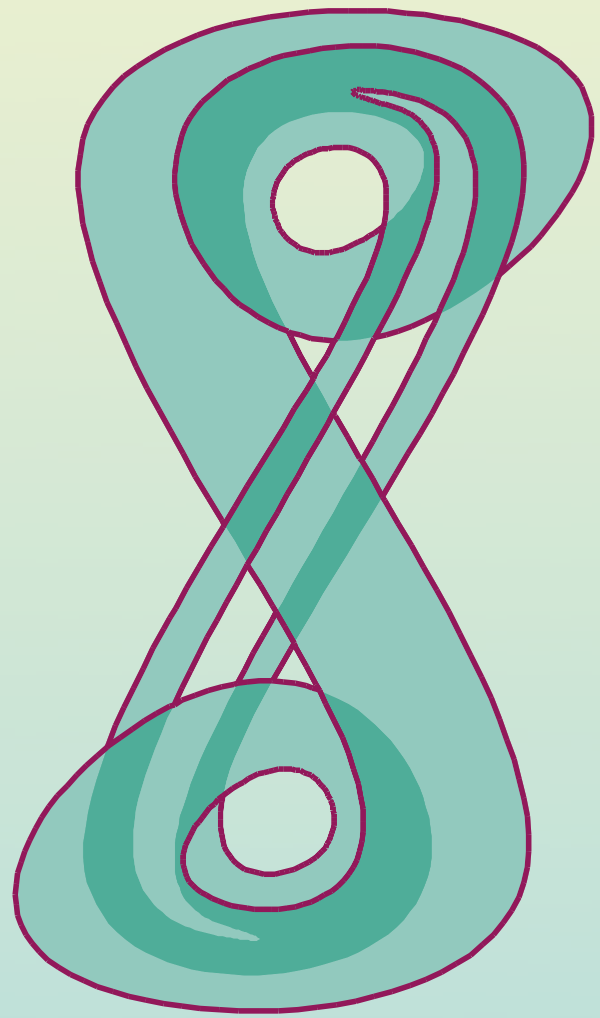
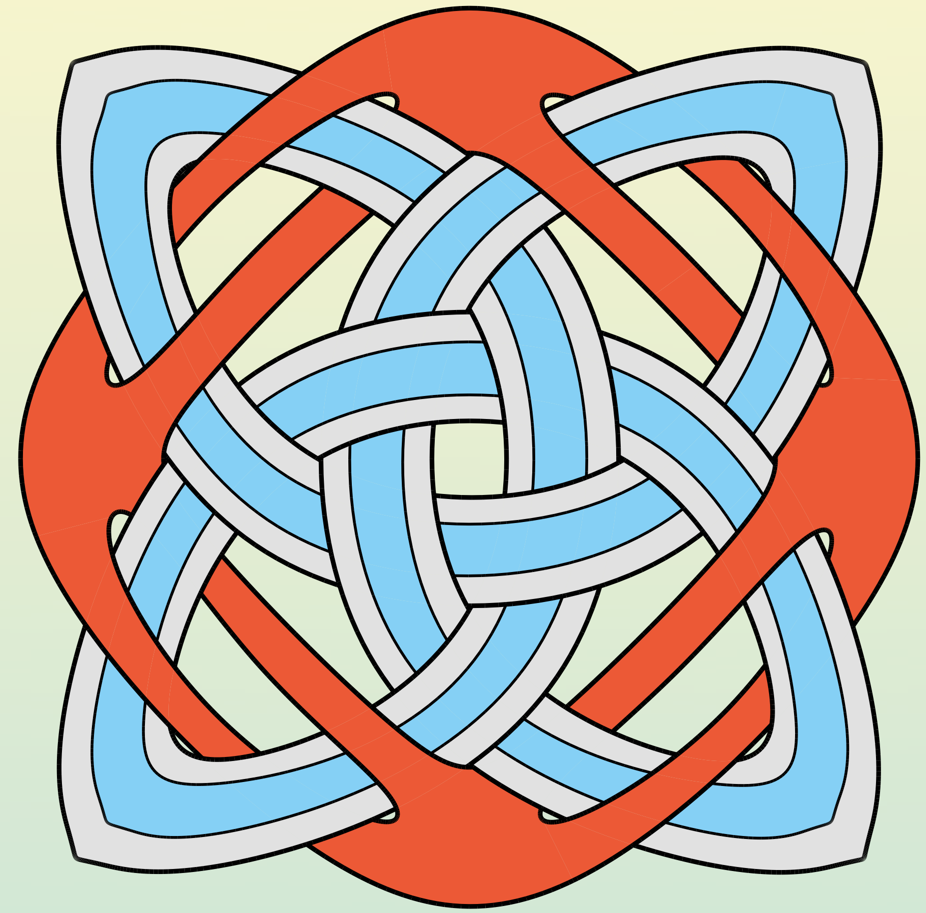
Talk Overview

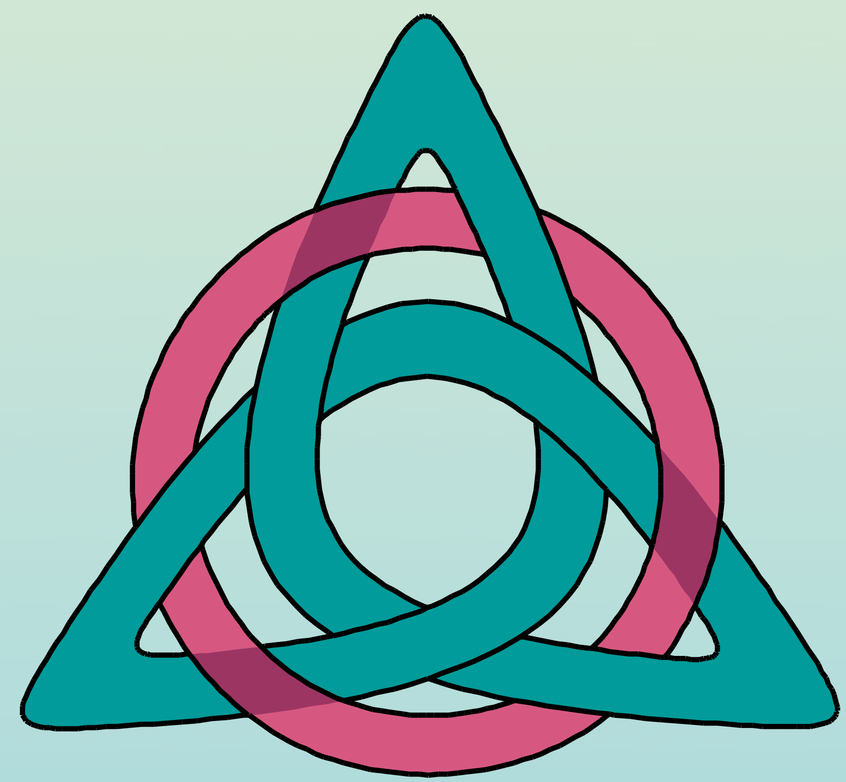
- **Introduction, Current State-of-the-Art**
- Druid Description, Usage
- Finding Legal Labelings
- Crossing-State Equivalence Classes
- Conclusions

Interwoven 2½D Scenes









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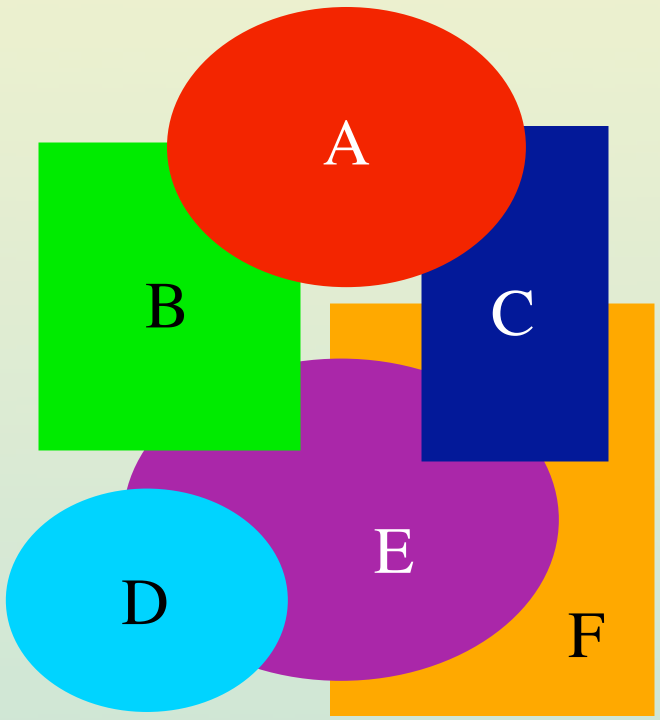
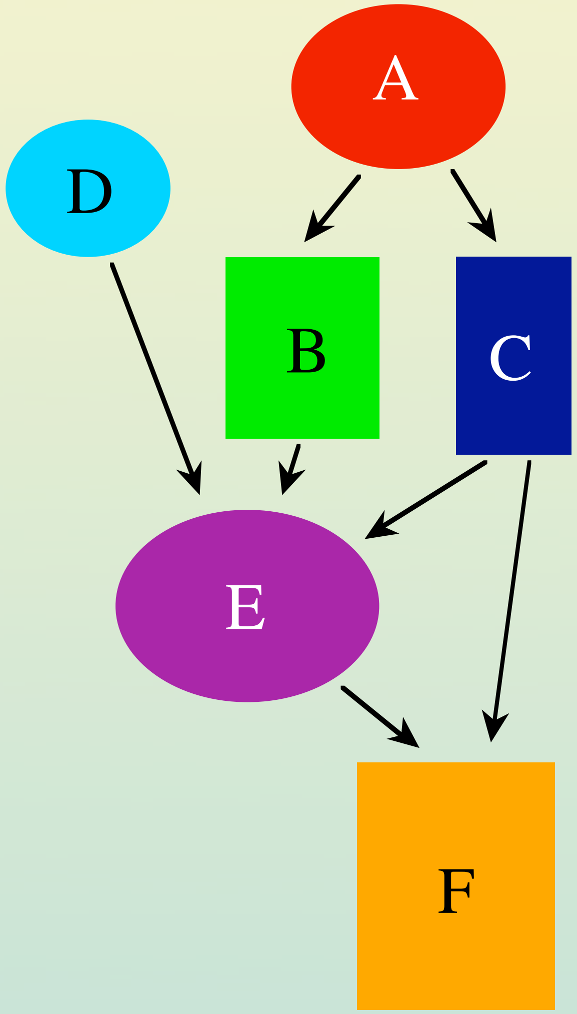
Introduction

Existing drawing programs:

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





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

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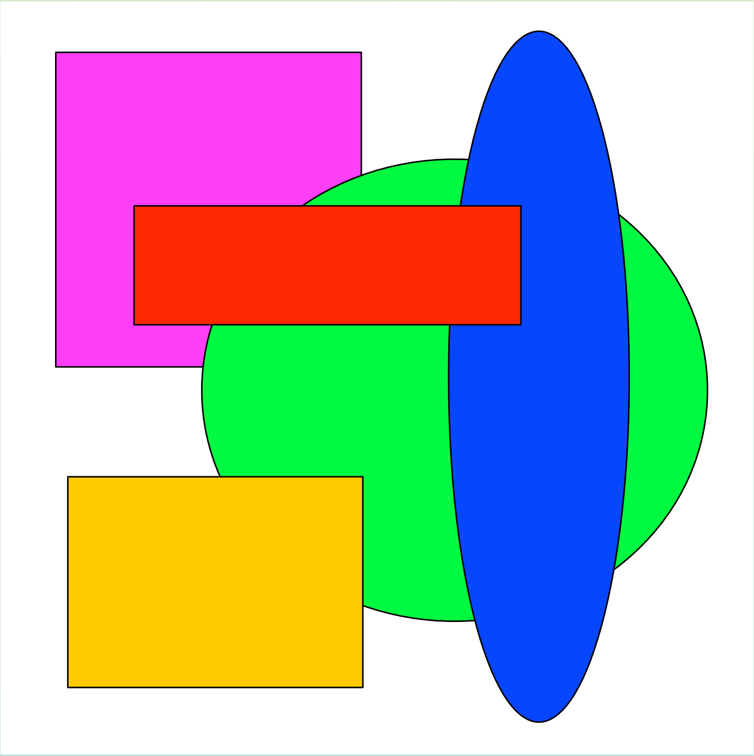
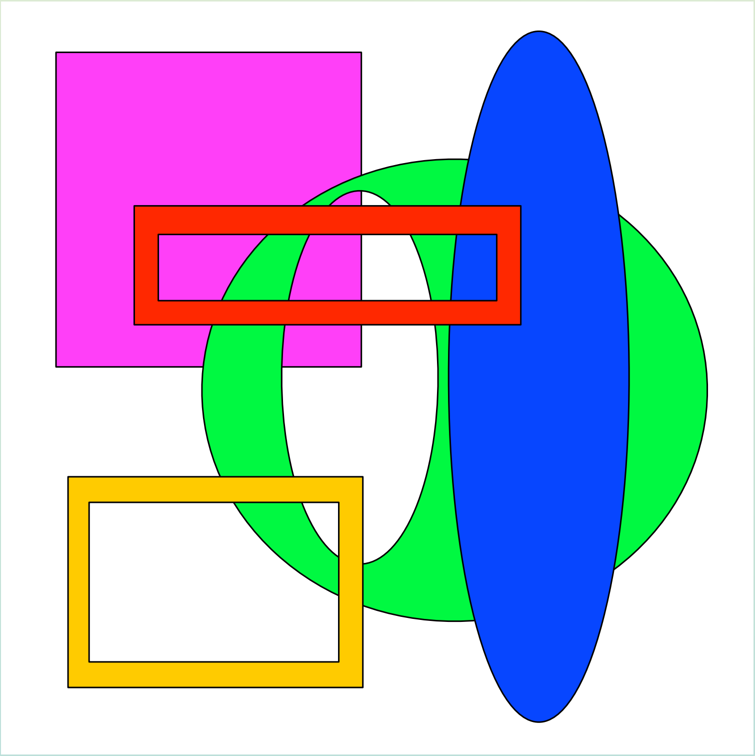
Existing Drawing Programs

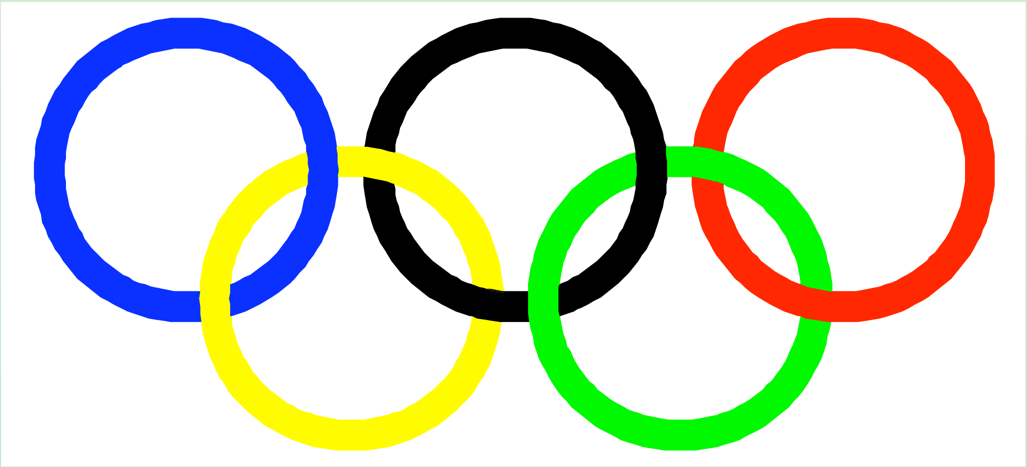
Noninterwoven layers

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

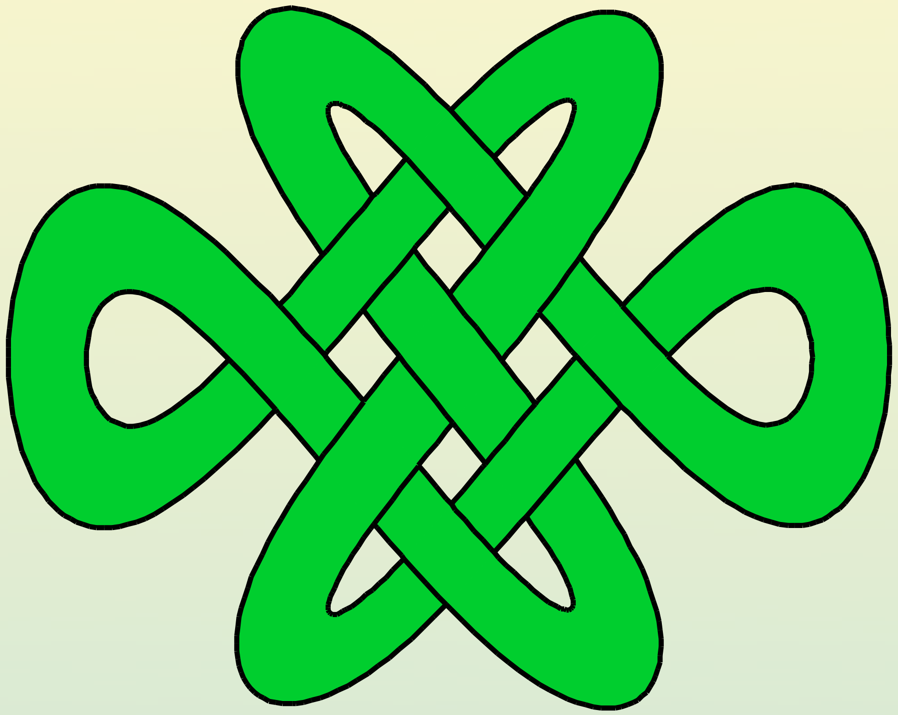
Do not span the full space of ***2½D scenes***.

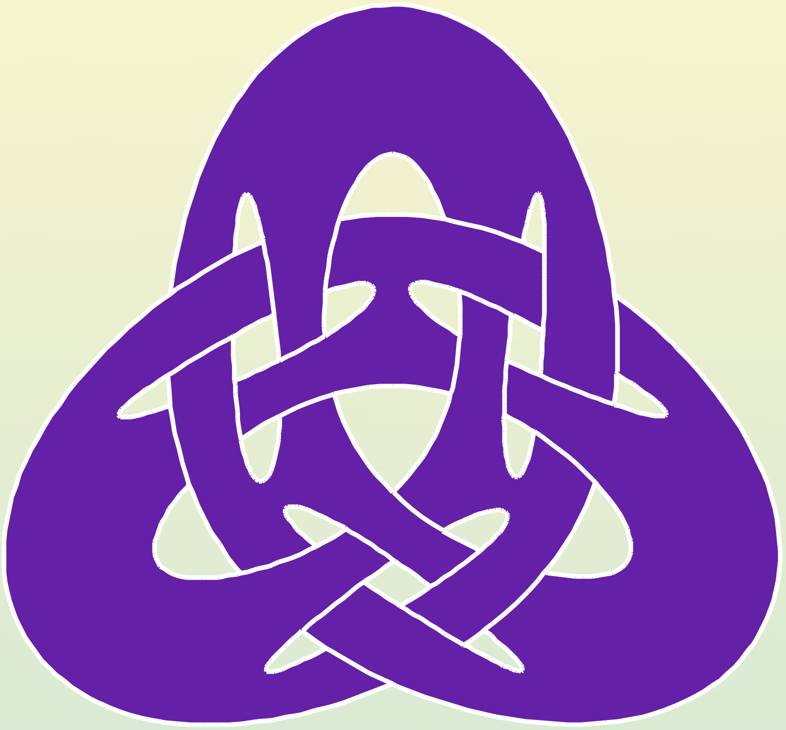


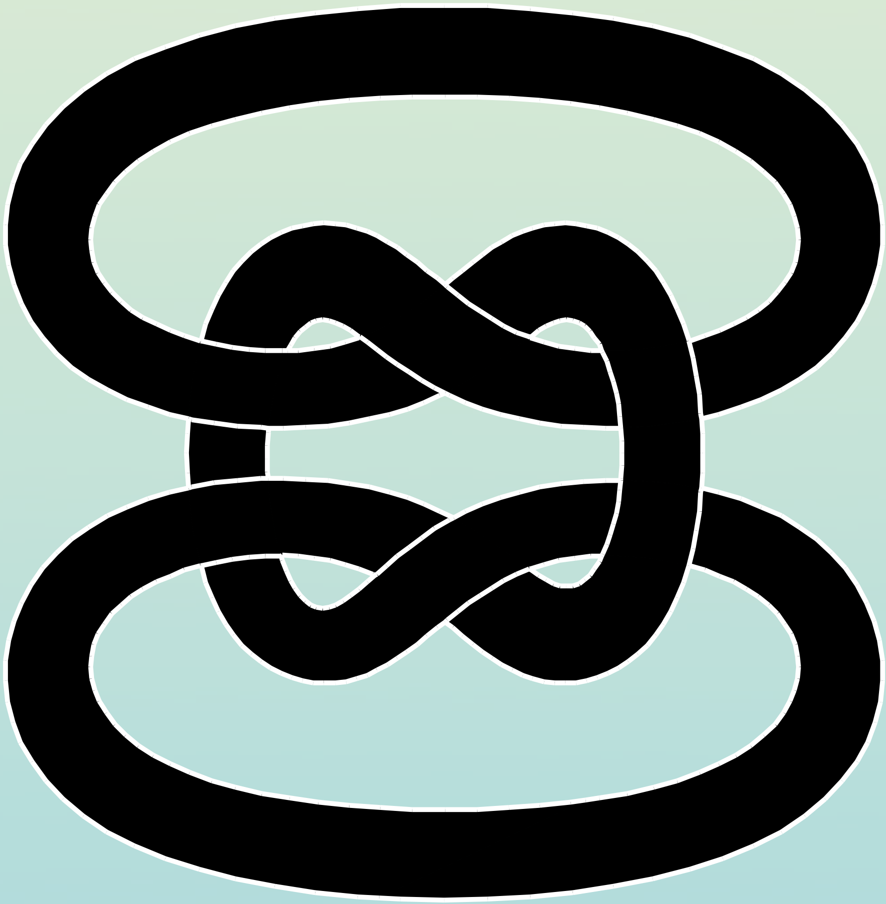




Knots vs. Interwoven Surfaces







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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*

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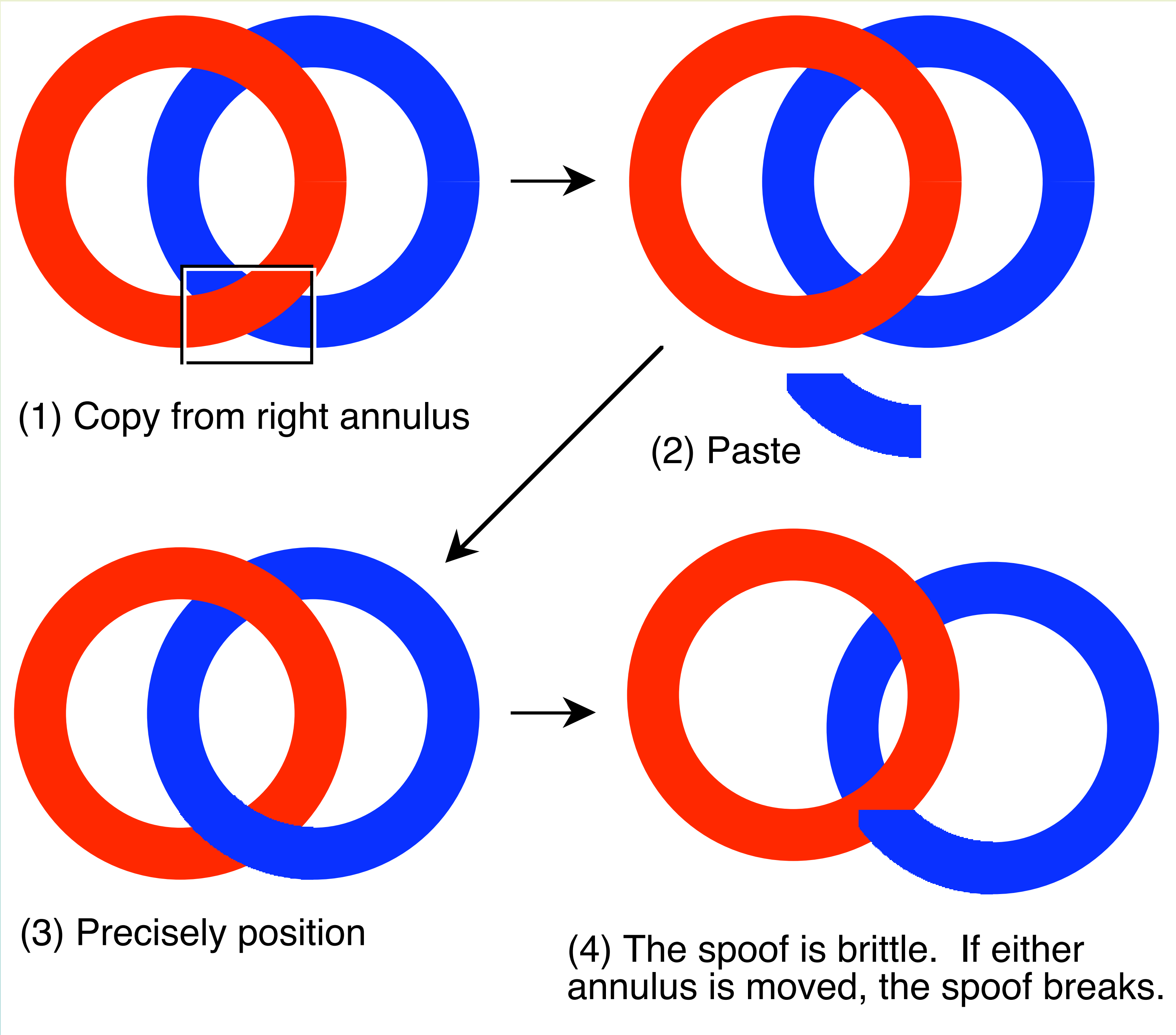
Spoofs

A layered arrangement that produces the illusion of interwoven surfaces



- Tedious to construct
- Tedious to maintain

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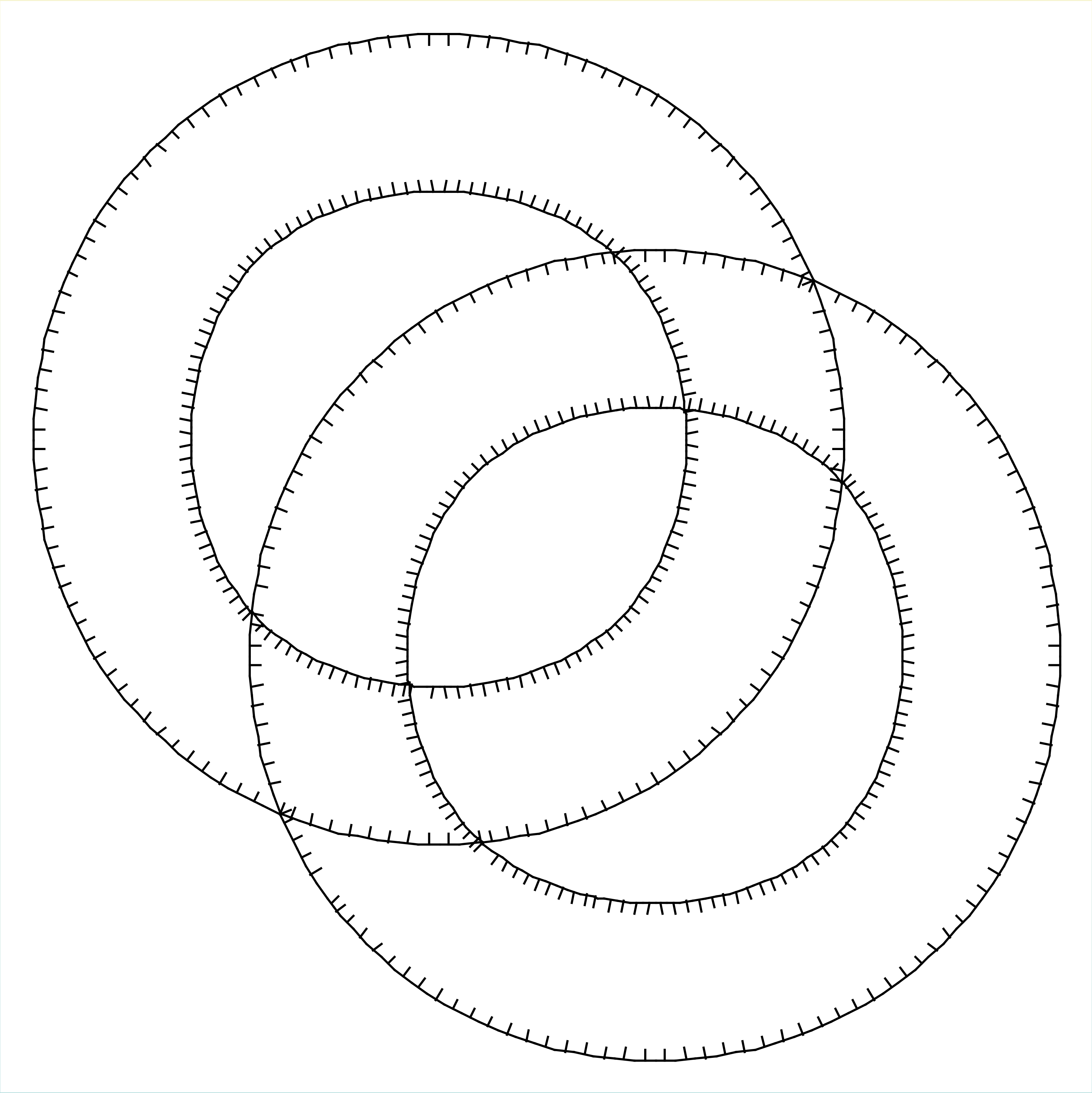
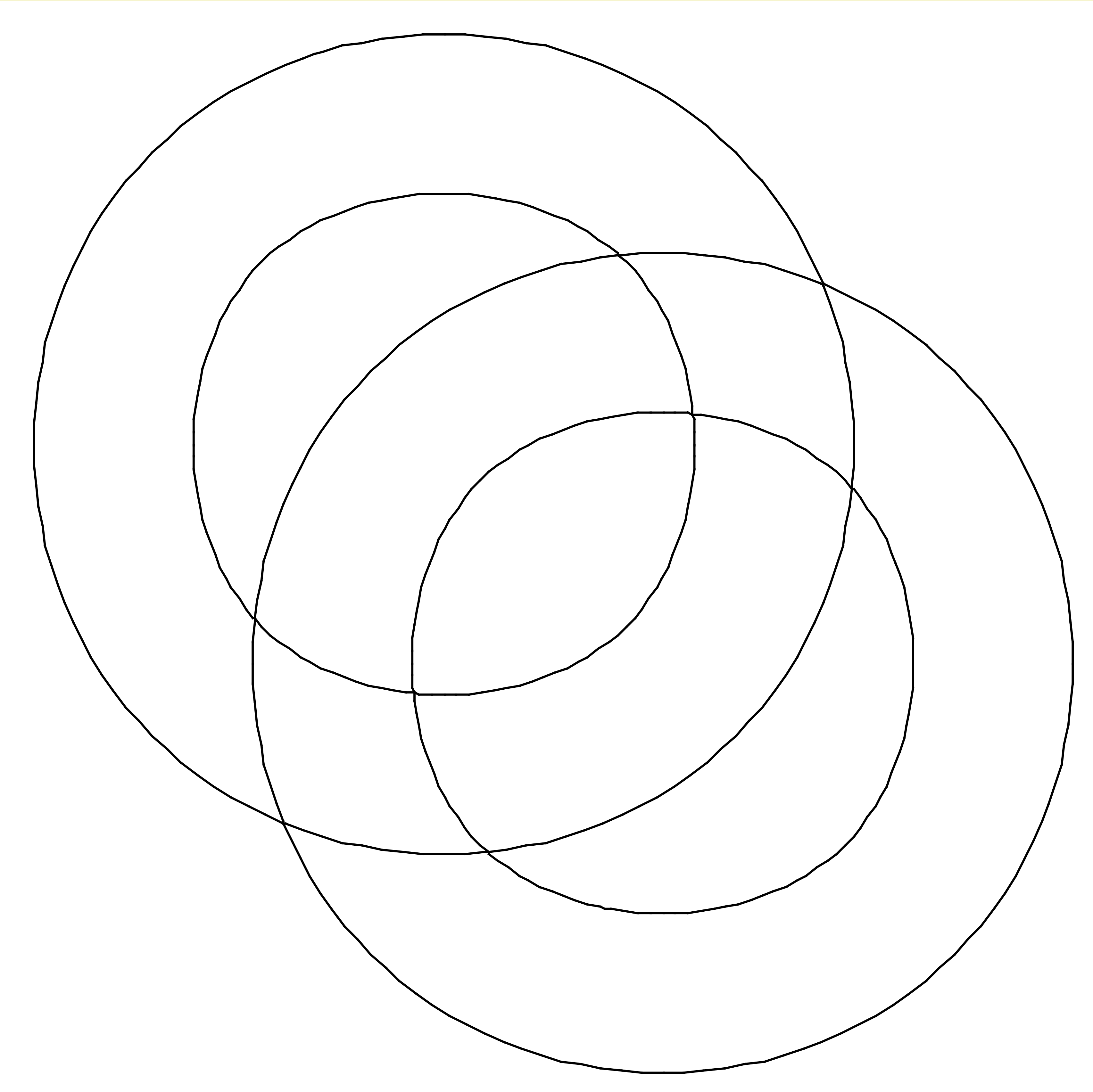
Adobe Illustrator Method



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

Adobe Illustrator Method



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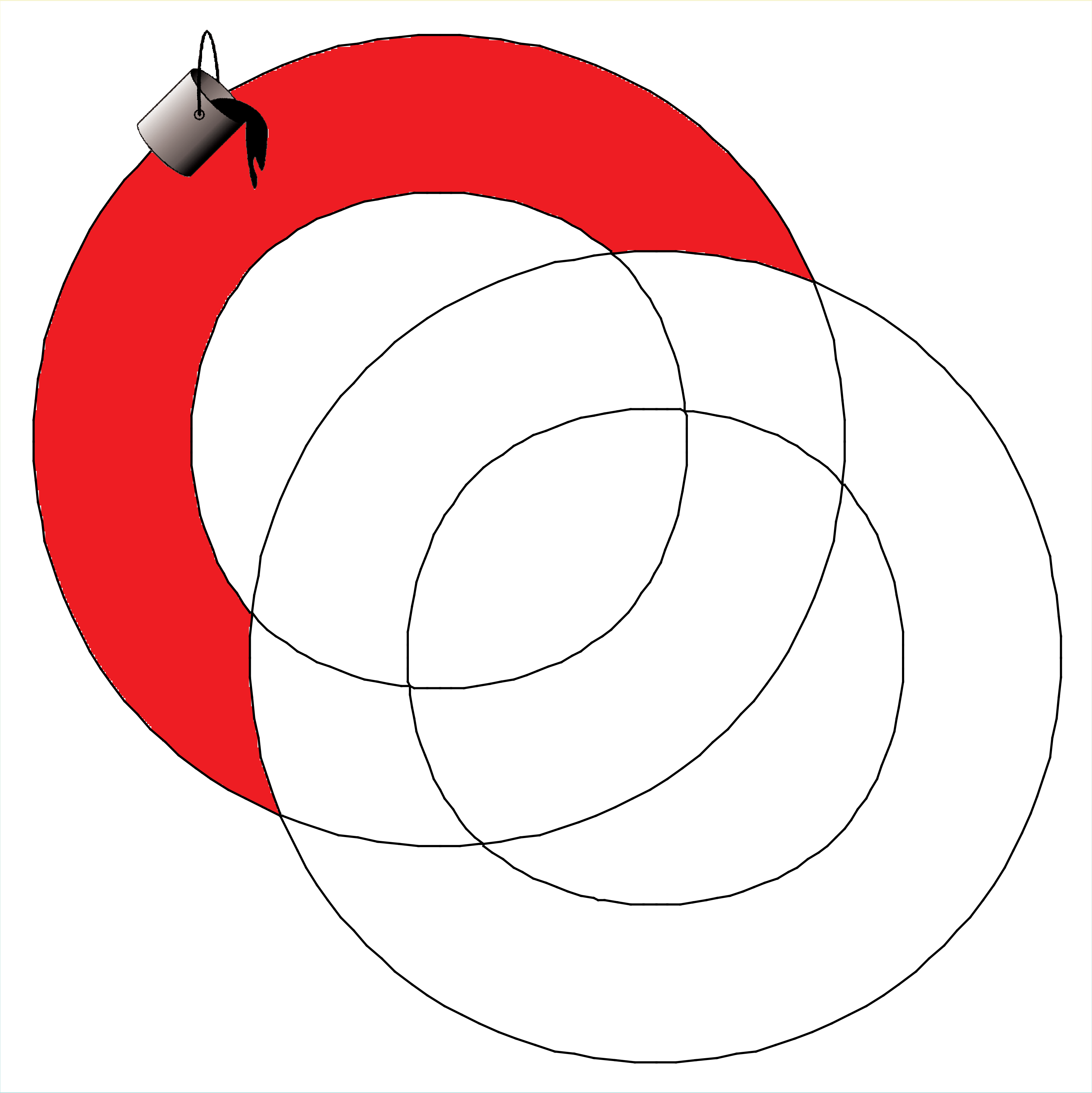

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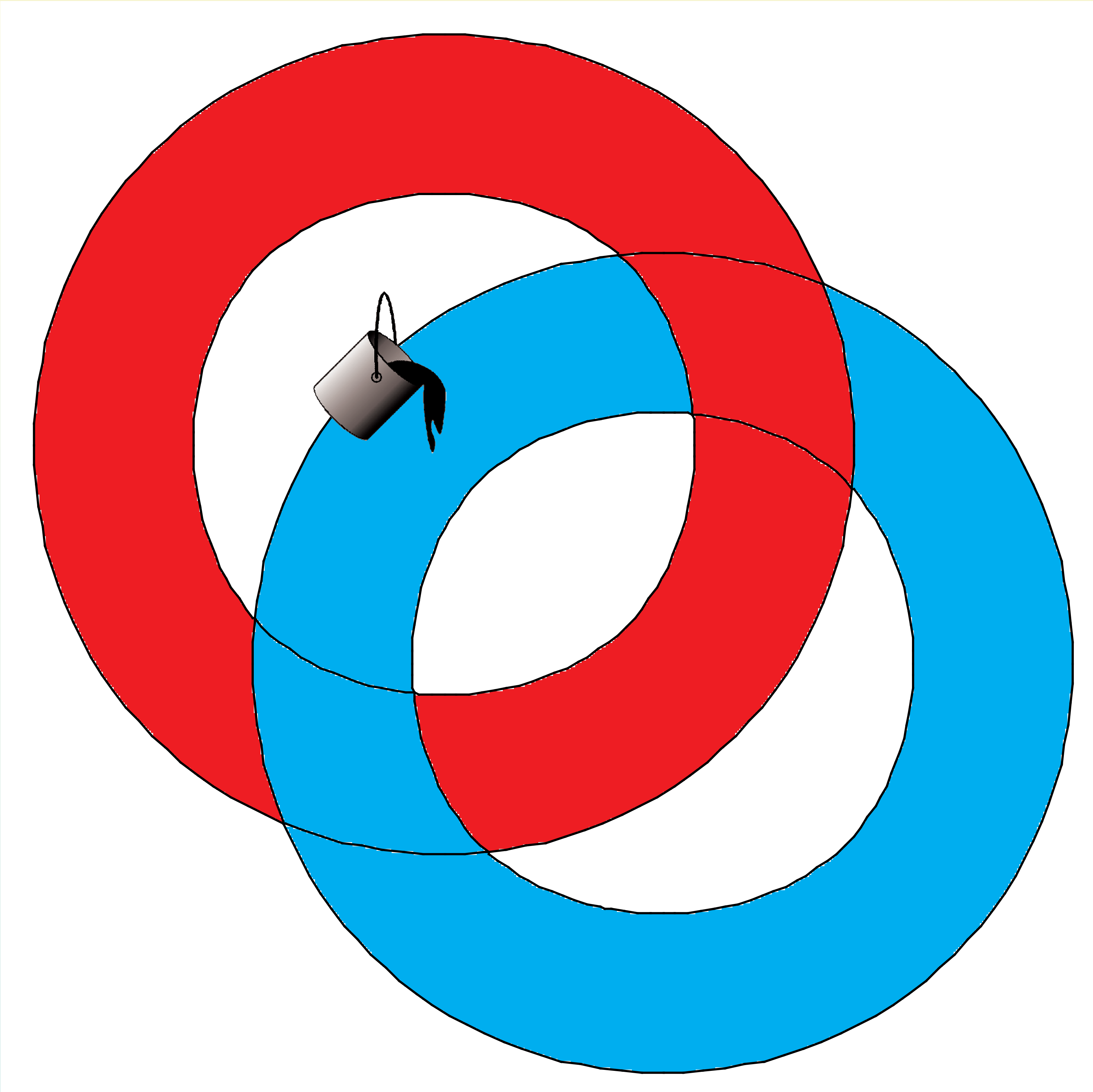

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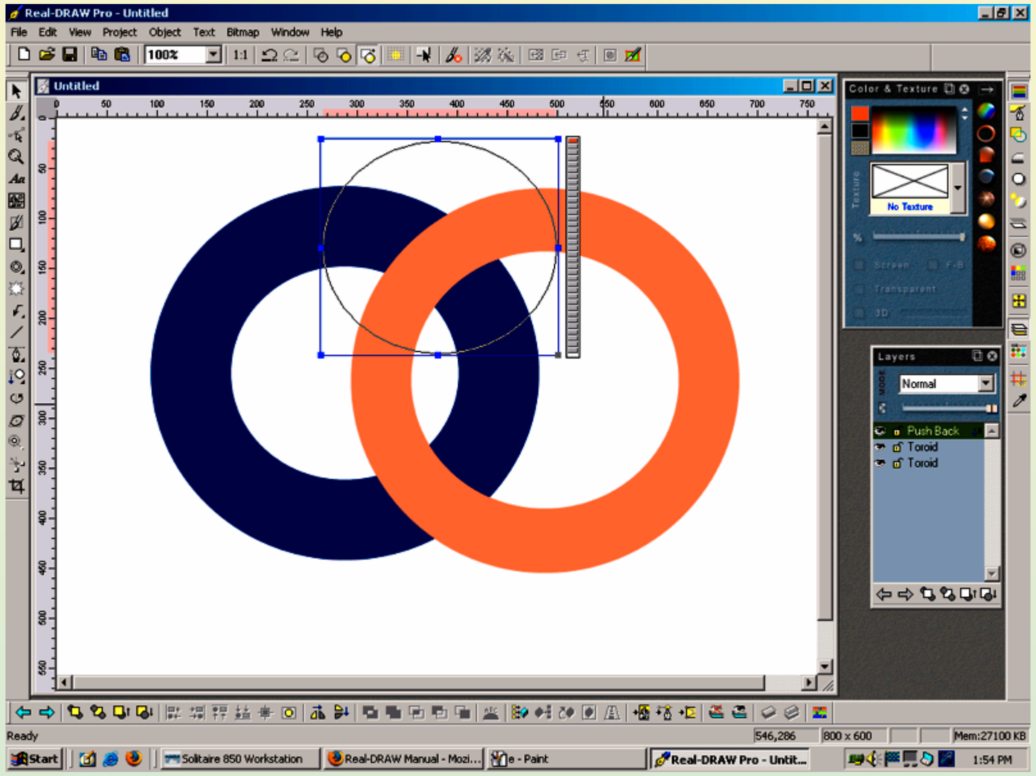
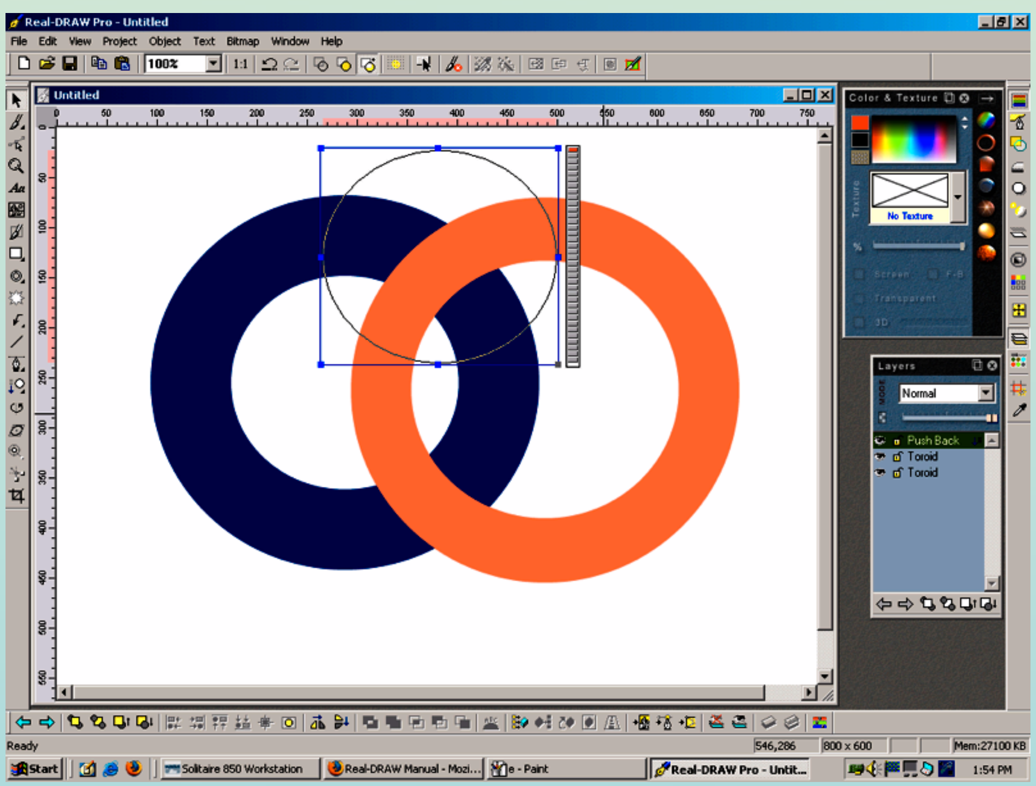
MediaChance Real-Draw Pro-3

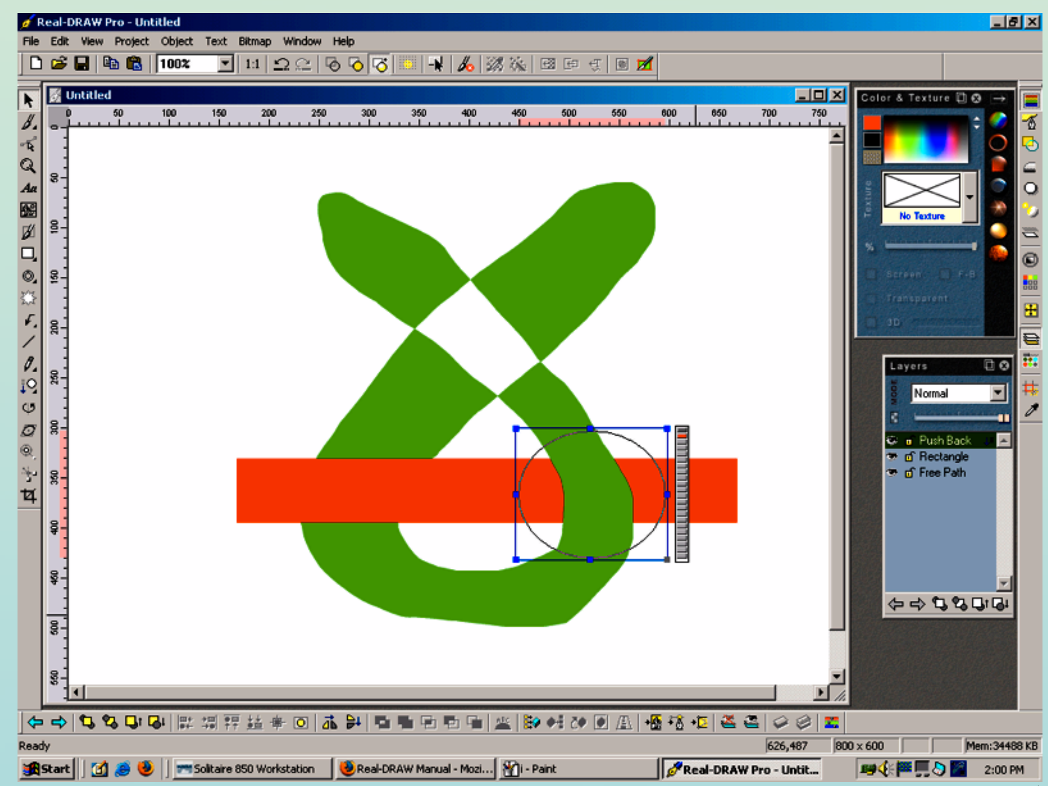


Push-back tool: The user can push the top layer down (figures left)

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

The right annulus is pushed down





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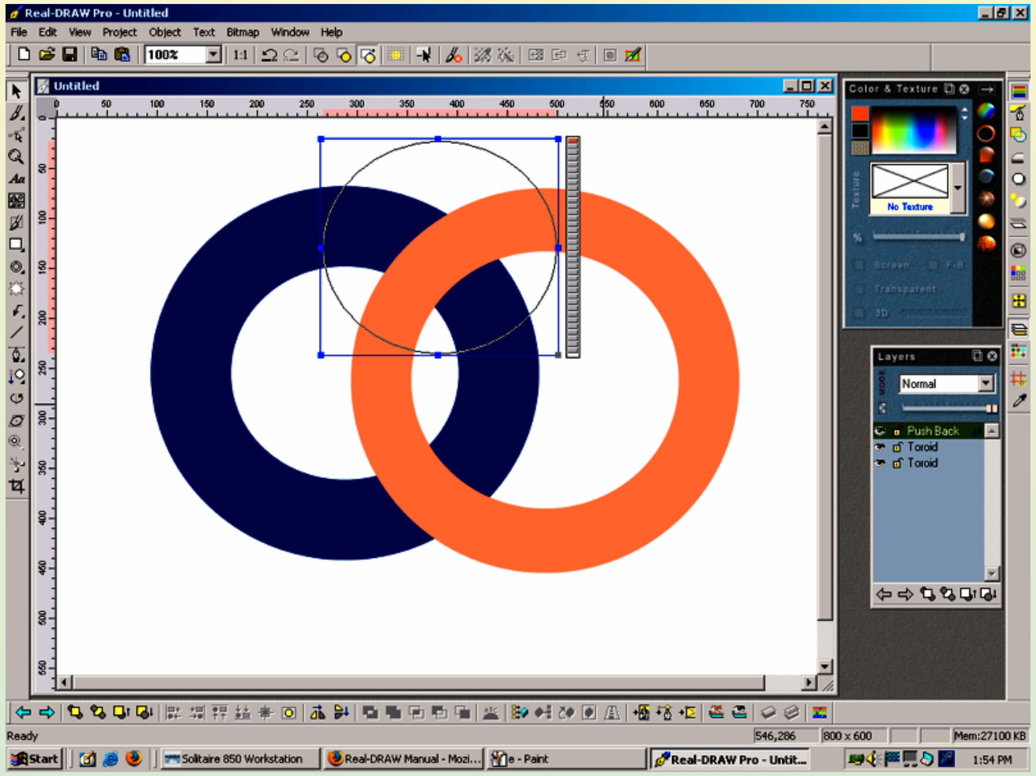
MediaChance Real-Draw Pro-3



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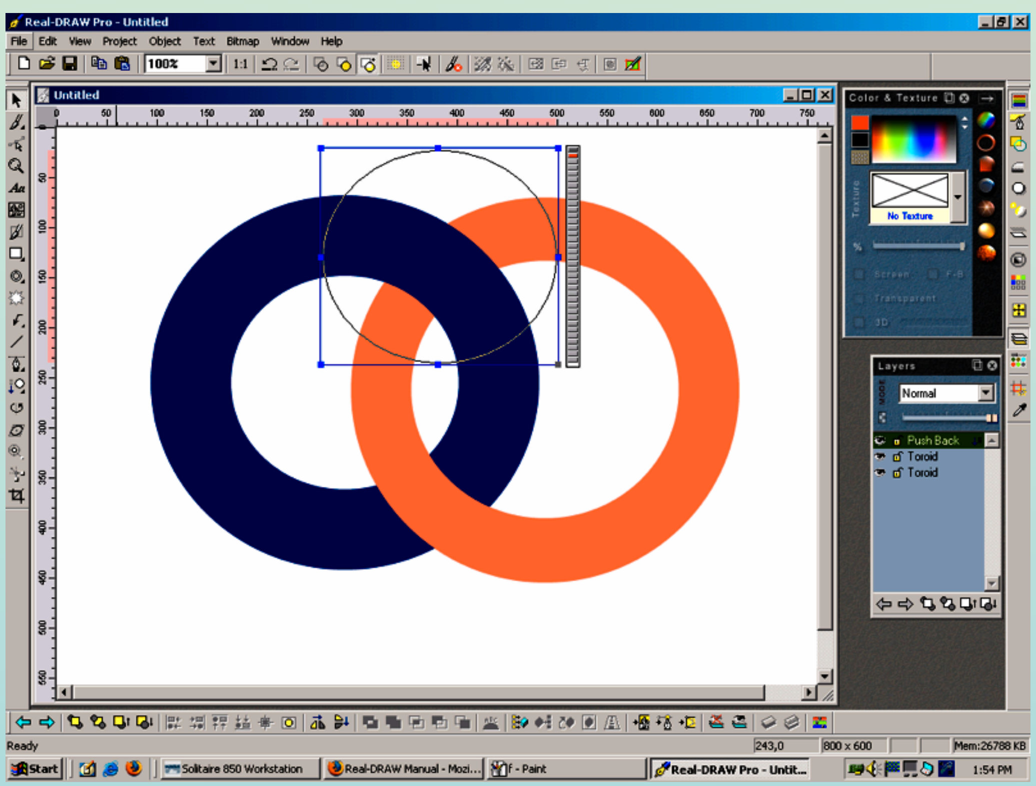

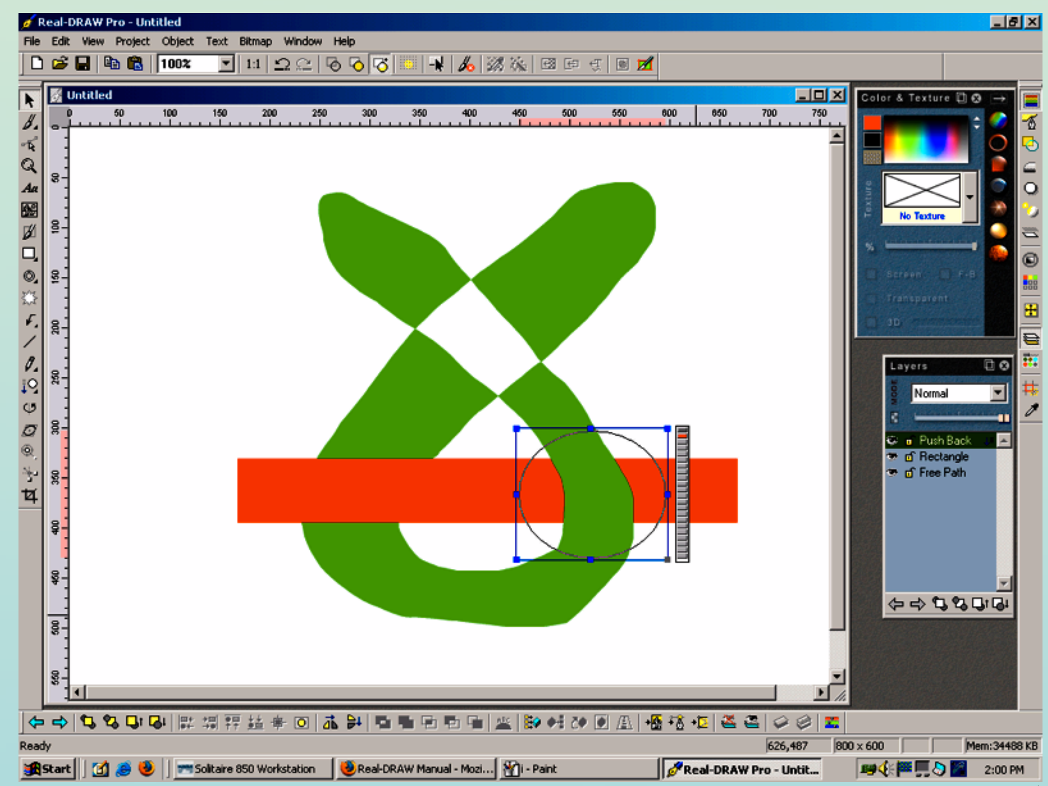

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Affordances

- ***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.

- Thus, the user's experience is of interacting with surfaces, not with pictures of surfaces.

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

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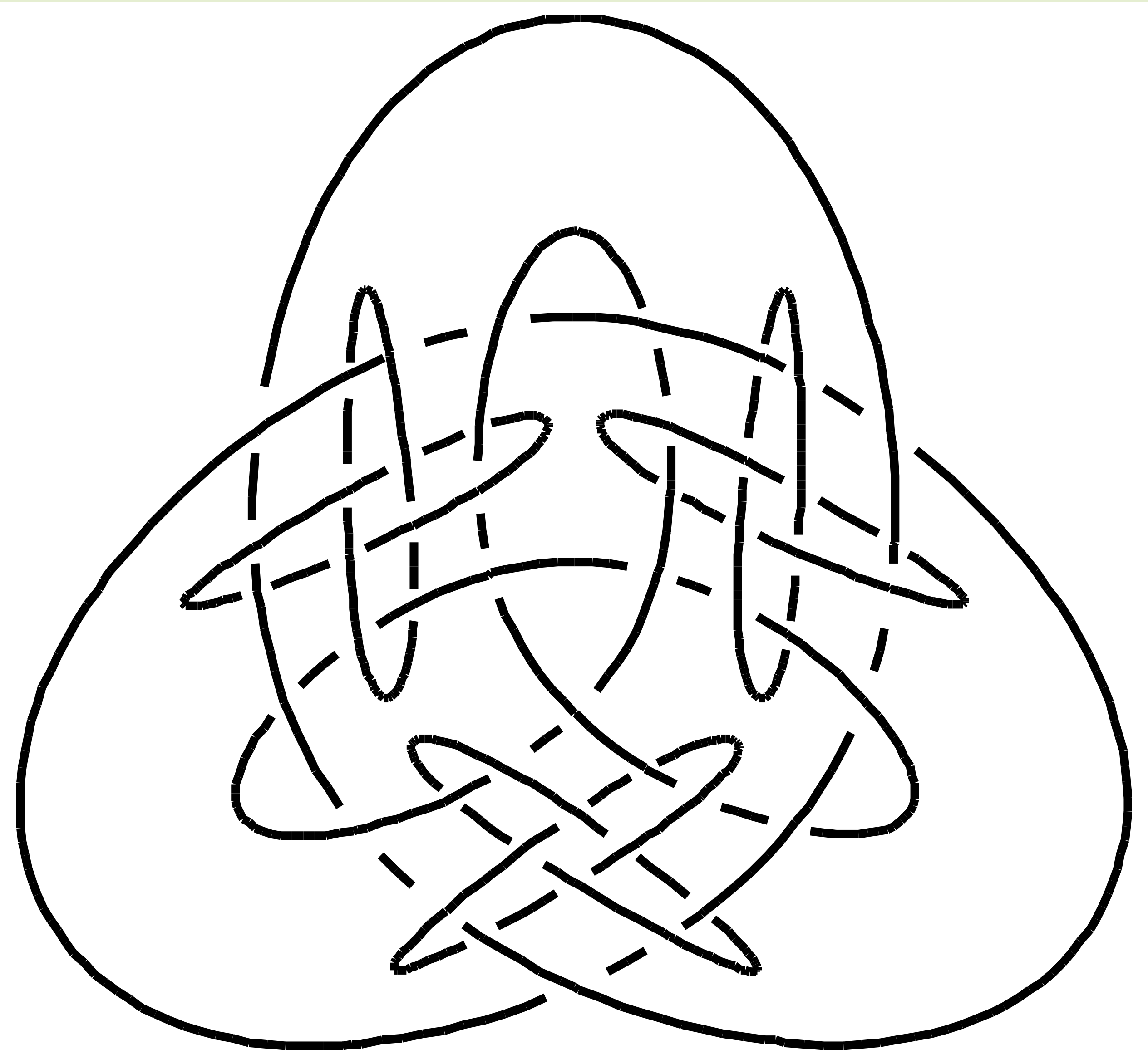
Druid's Representation

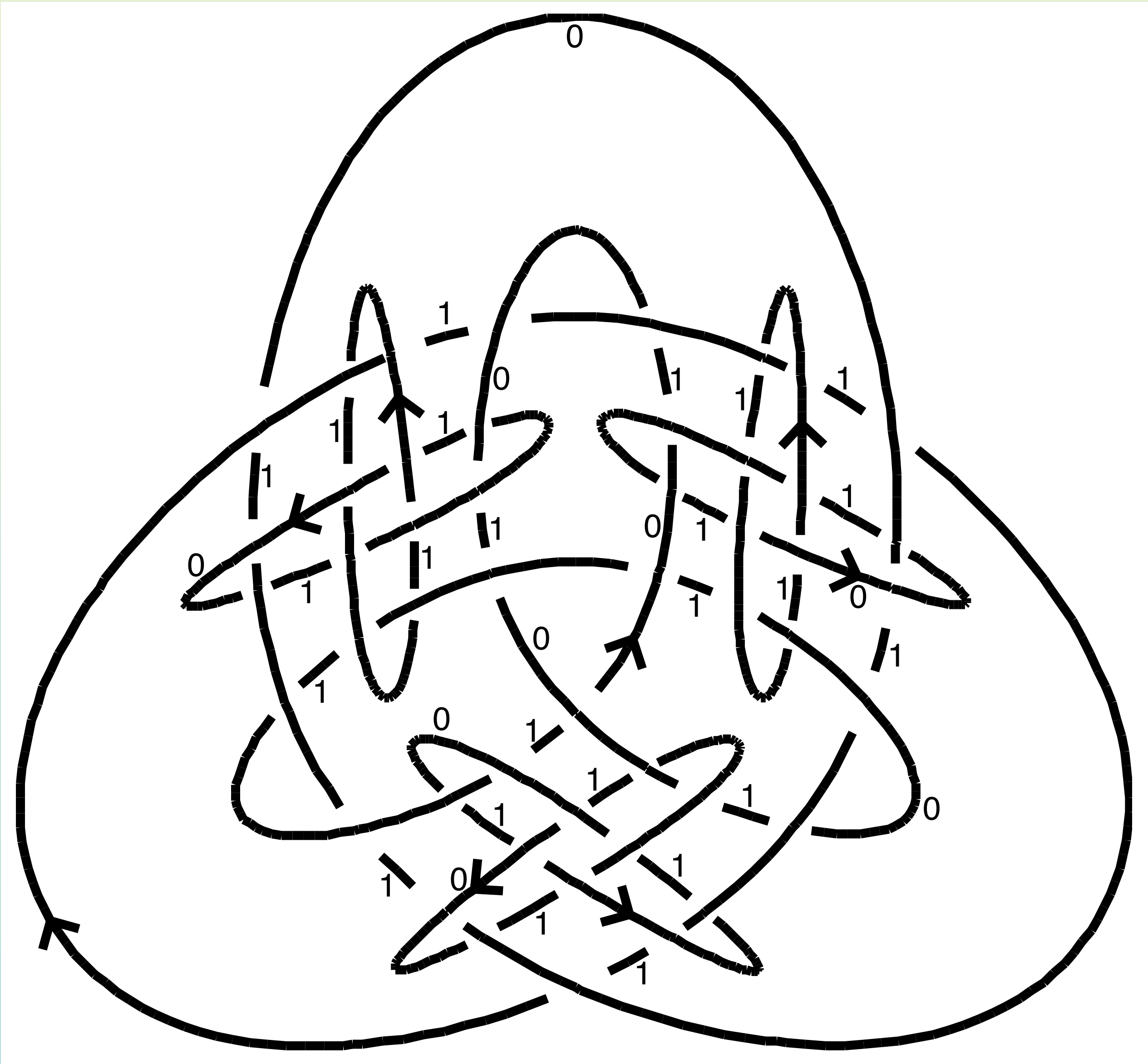
Knot-diagram:

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.

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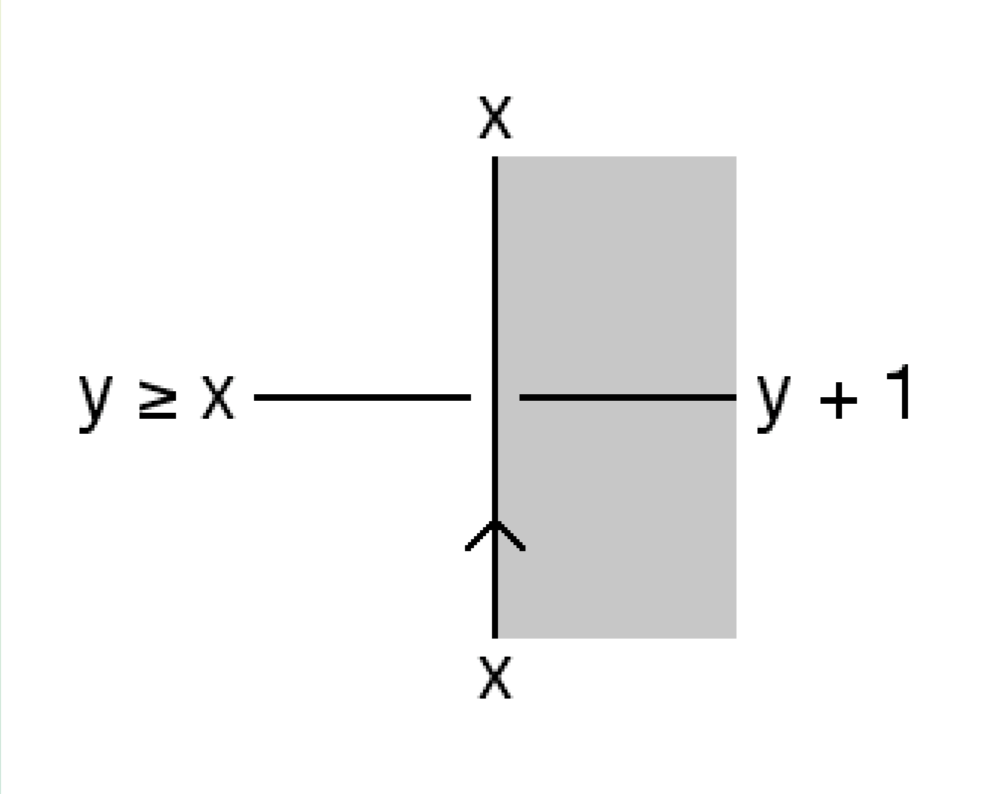
Labeling Scheme

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.

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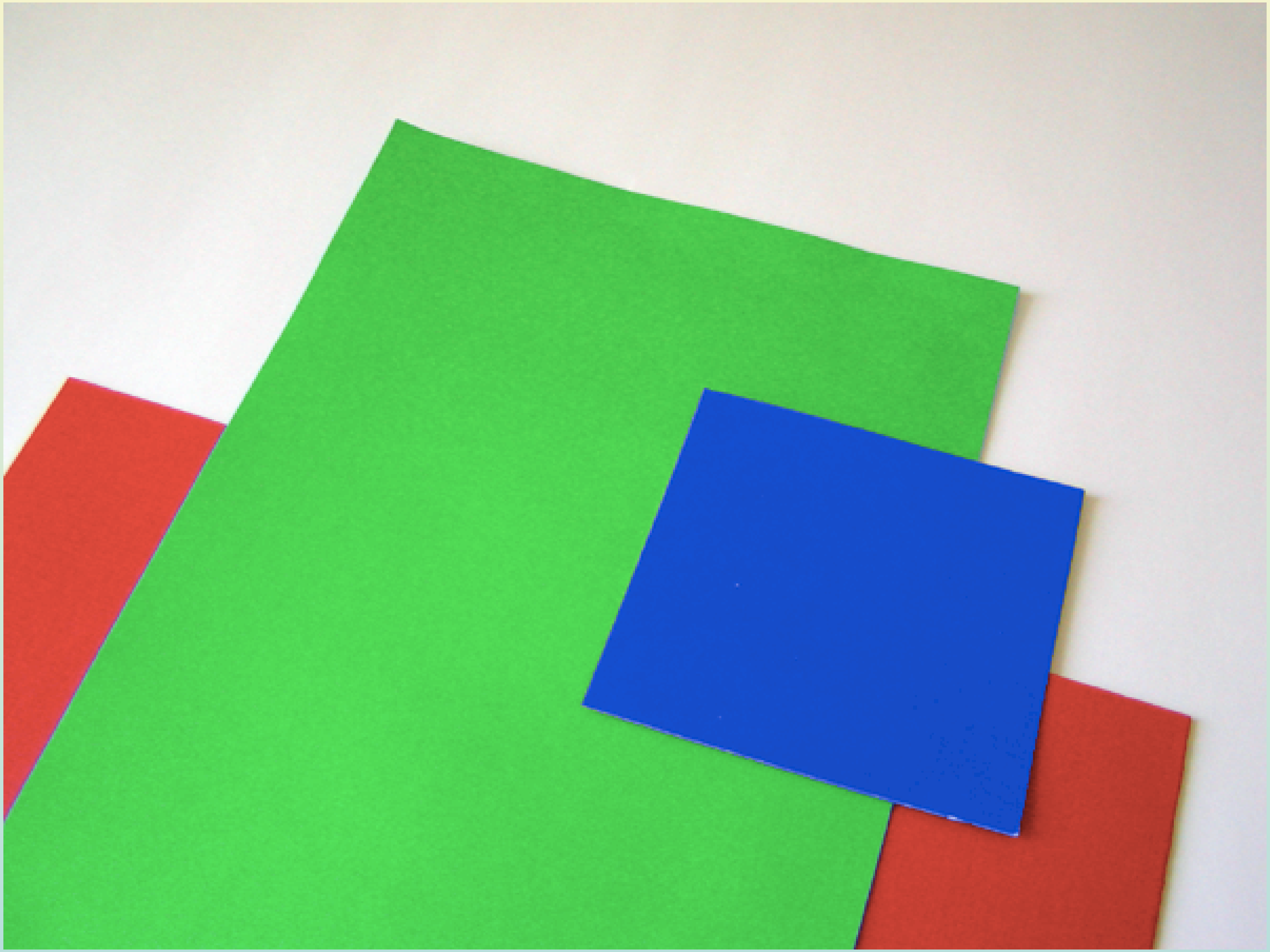
Labeling Scheme Justification



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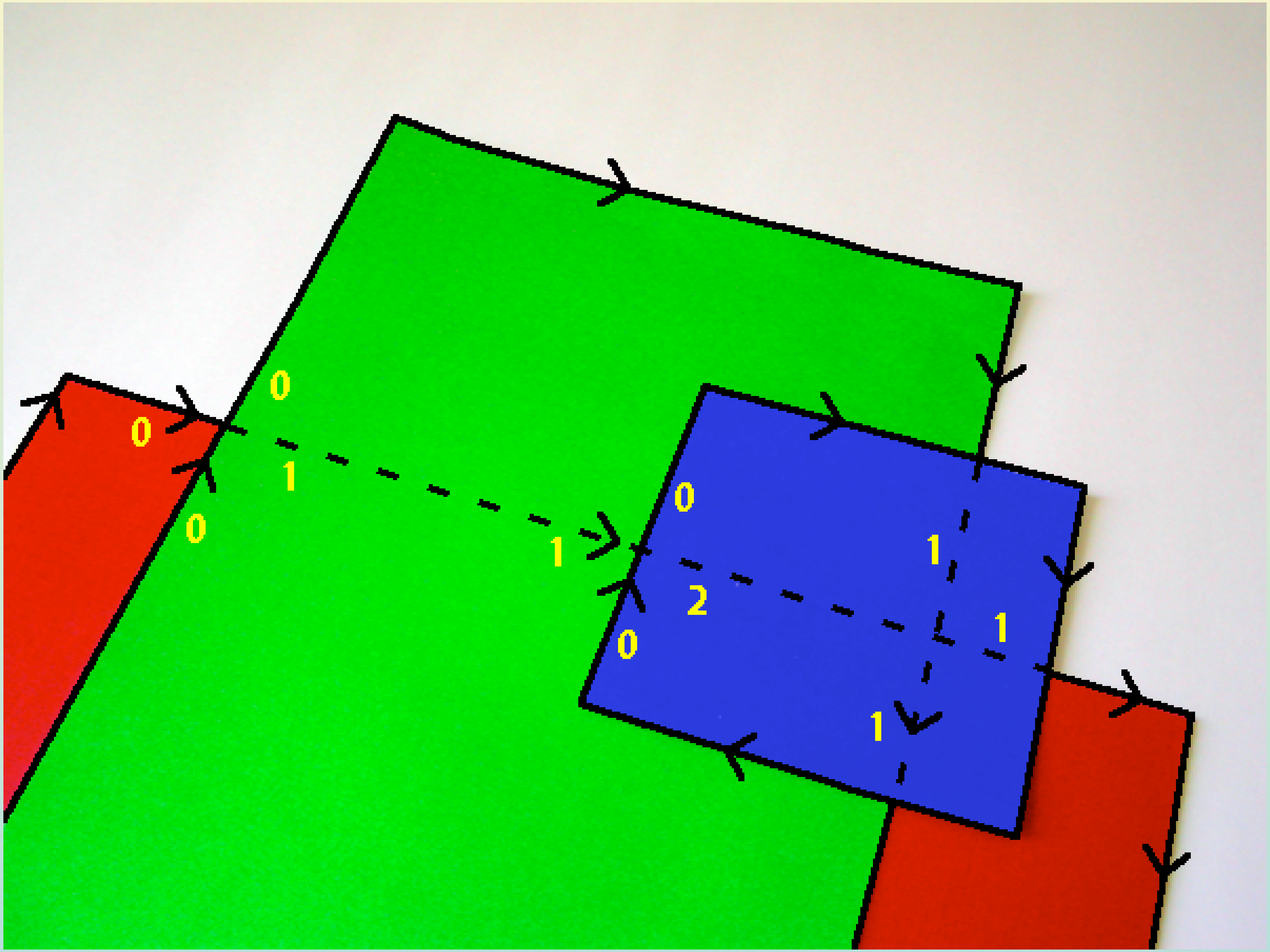
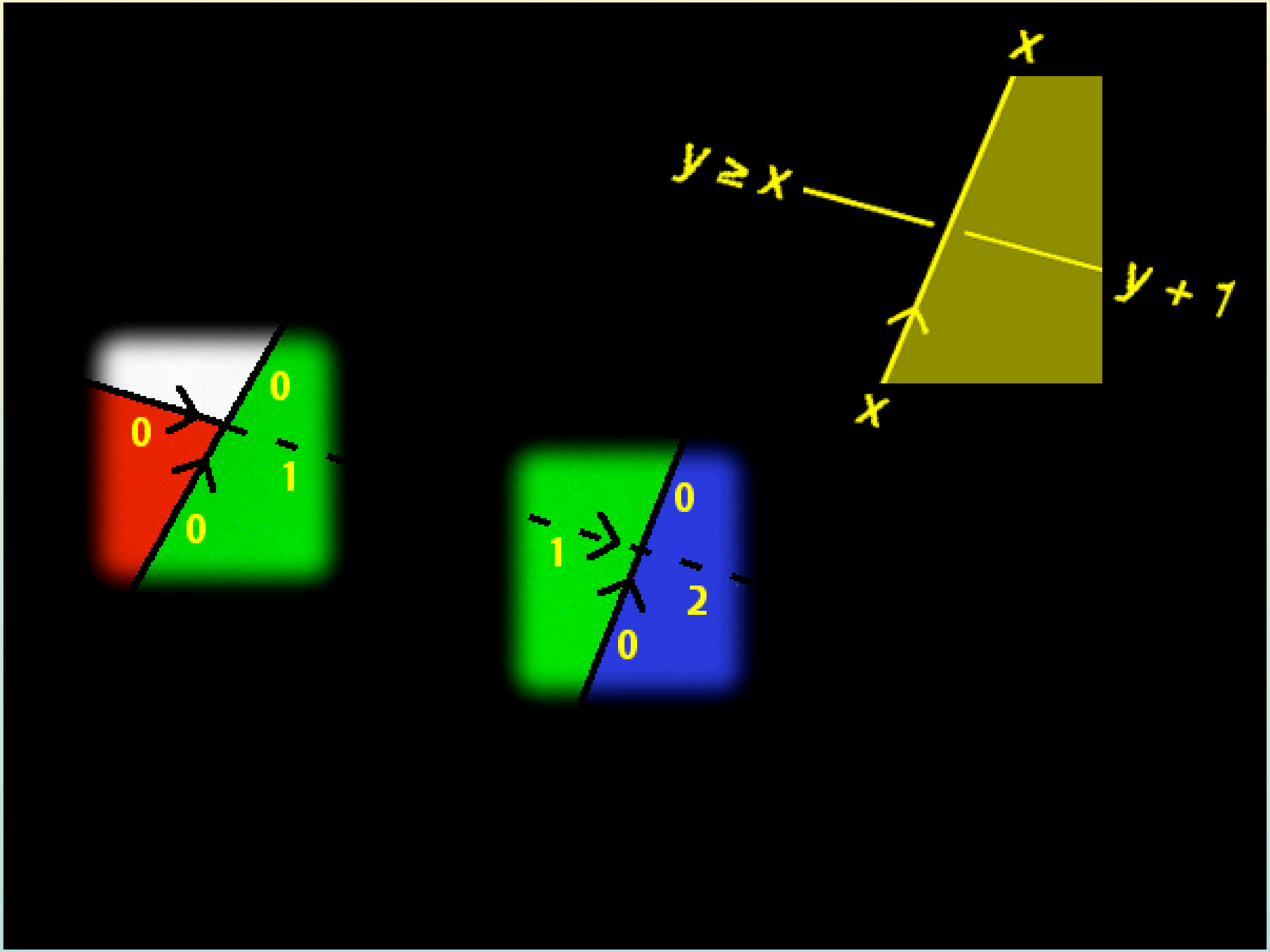
Labeling Scheme Justification



Labeling Scheme Justification



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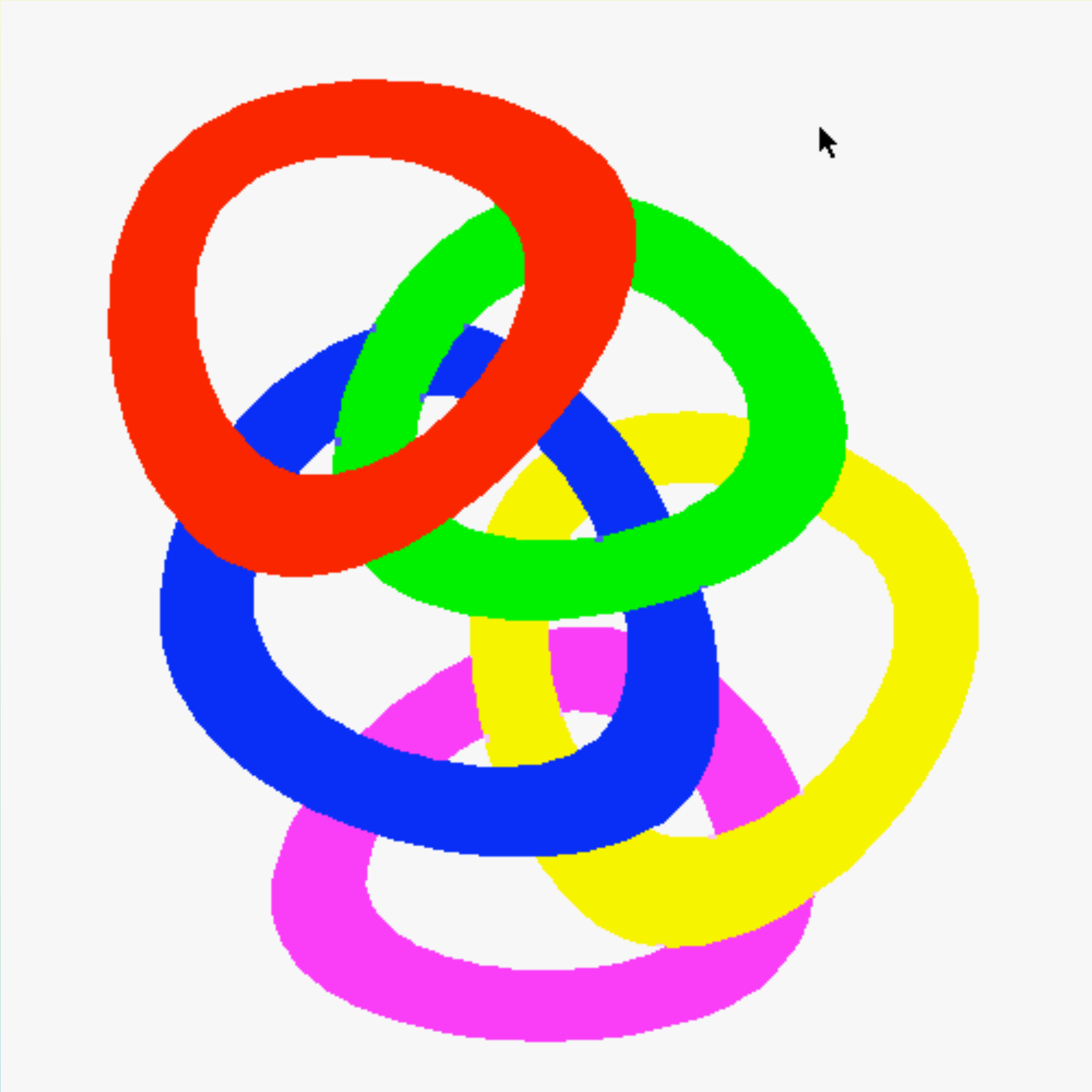
Using *Druid*

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

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Effects of Interactions on the Labeling

- Creation & deletion of crossings
- Reordering of crossings around boundaries
- Sign-of-occlusion flips
- Crossing-state flips
- Reshaping or dragging boundaries without causing topological changes

Effects of Interactions on the Labeling

Requiring ***labeling*** (topological change)

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

Requiring ***relabeling*** (topological change)

- Crossing-state flips

Maintaining labeling (no topological change)

- Reshaping or dragging boundaries without causing topological changes

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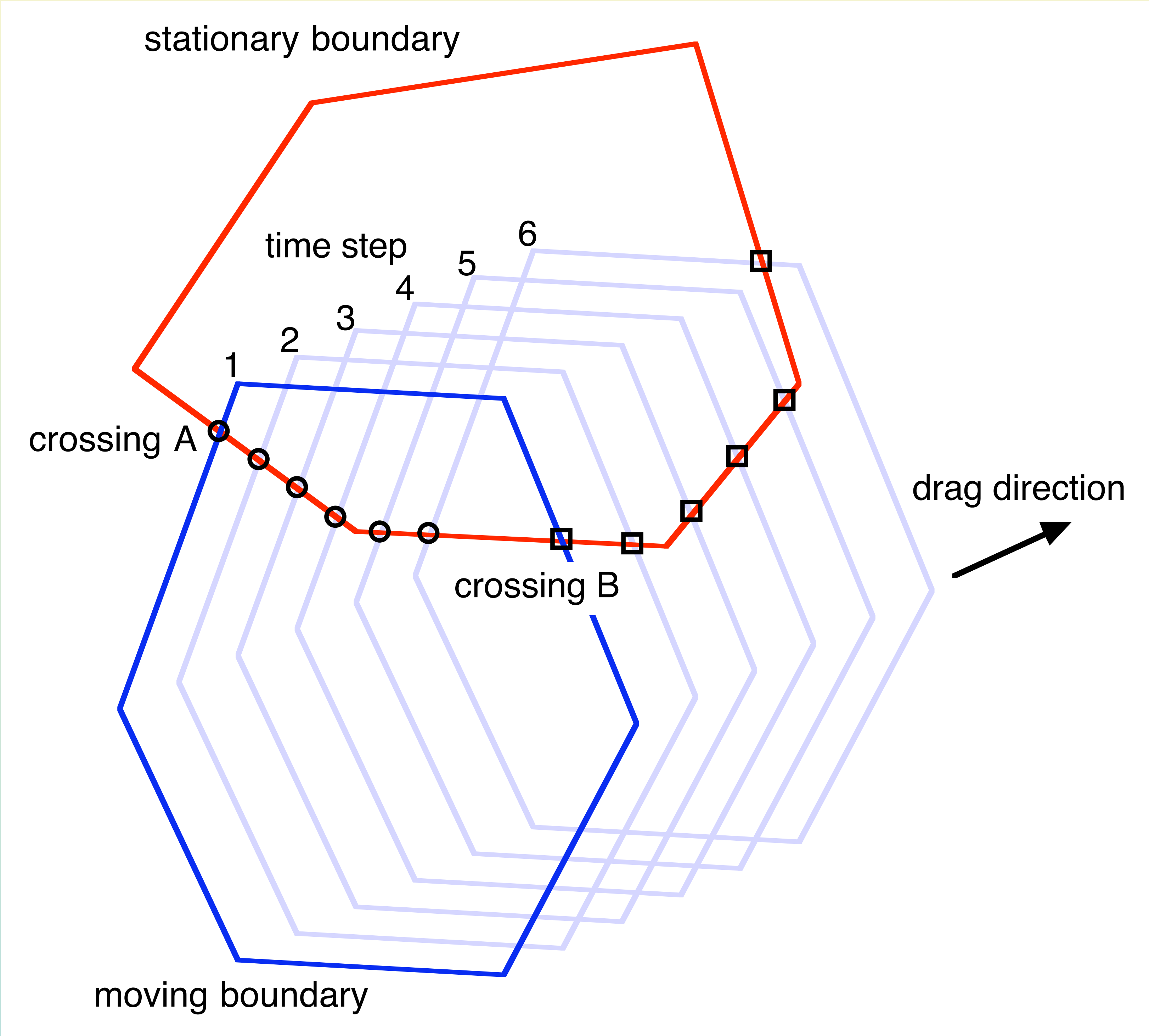
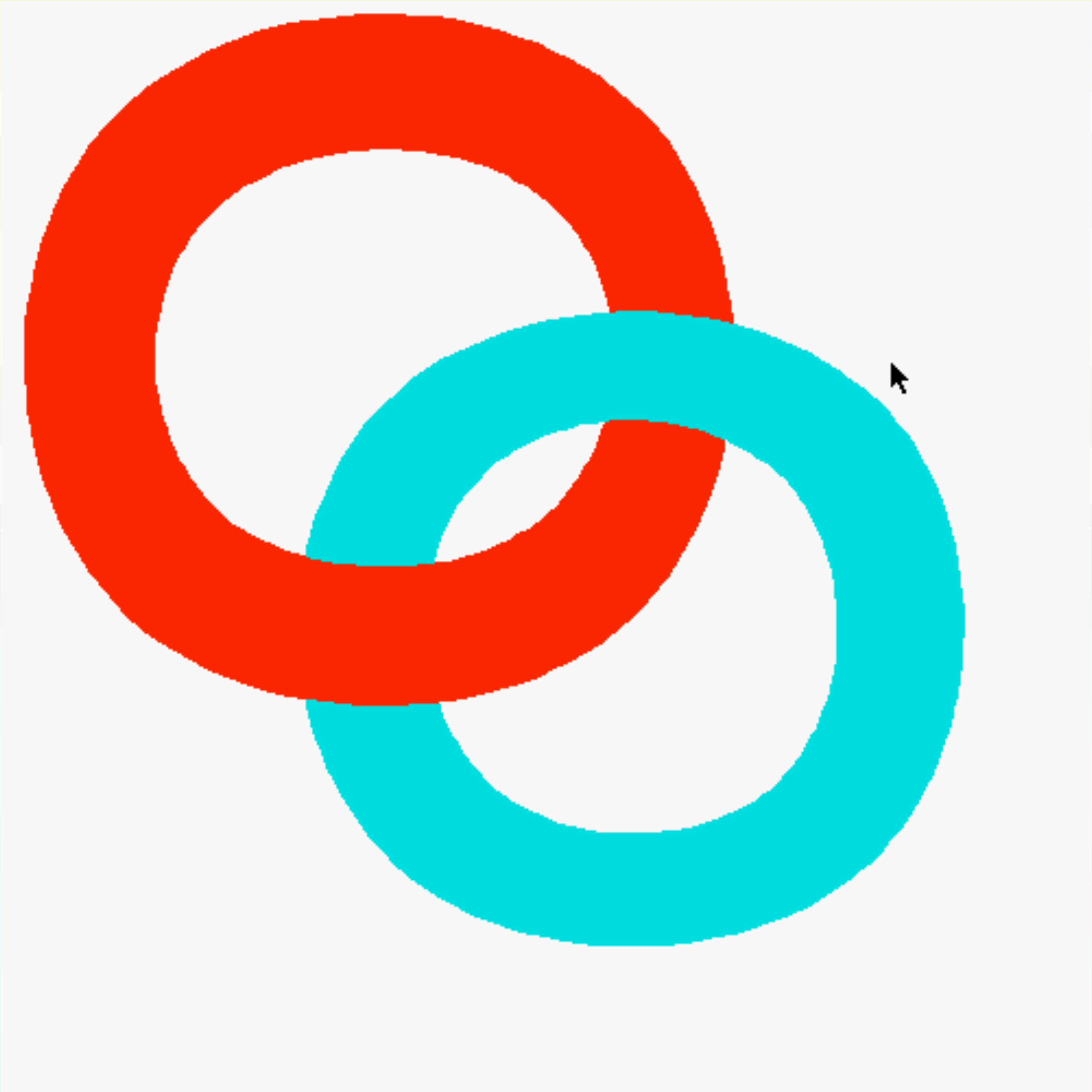
Crossing Projection

- 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.

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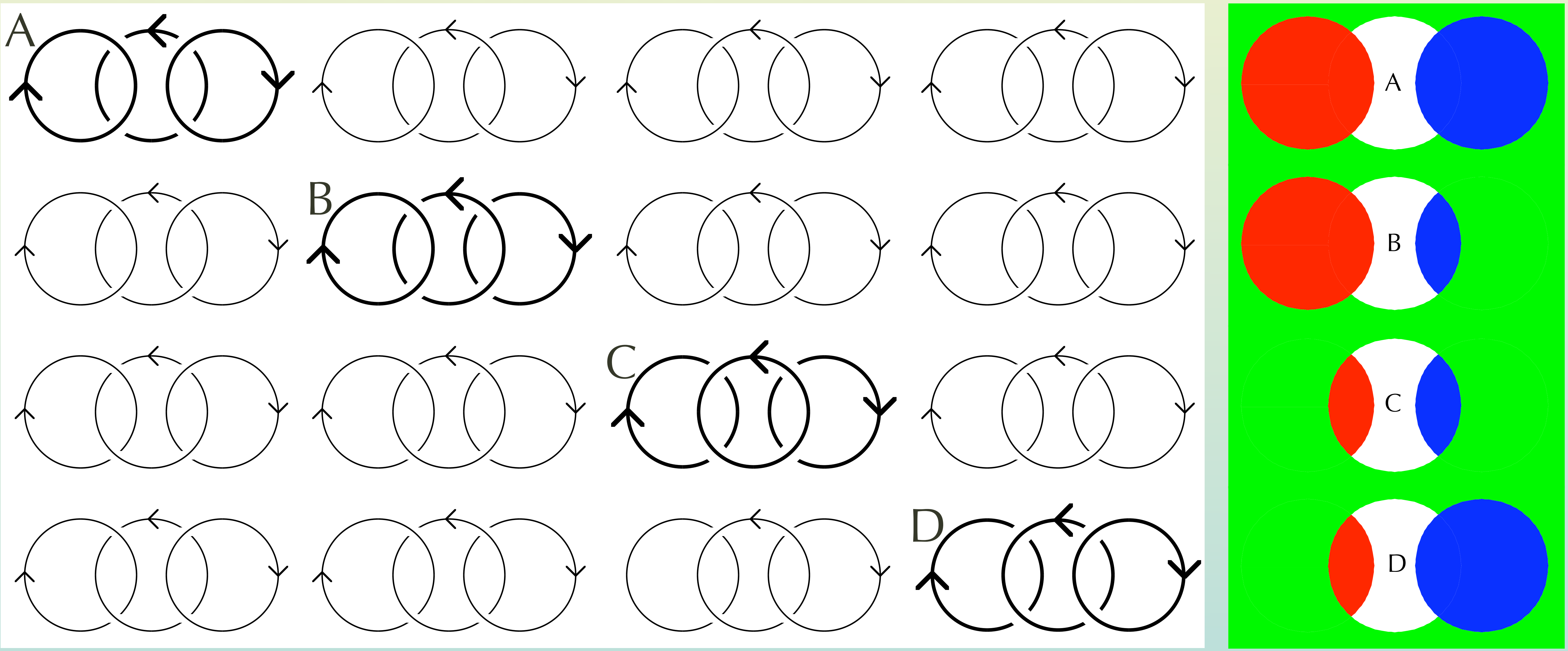
Finding a Legal Labeling

Labeling space: All possible labelings for a labeled knot-diagram. Labeling space size: 2^C



Druid maintains a legal labeling automatically.

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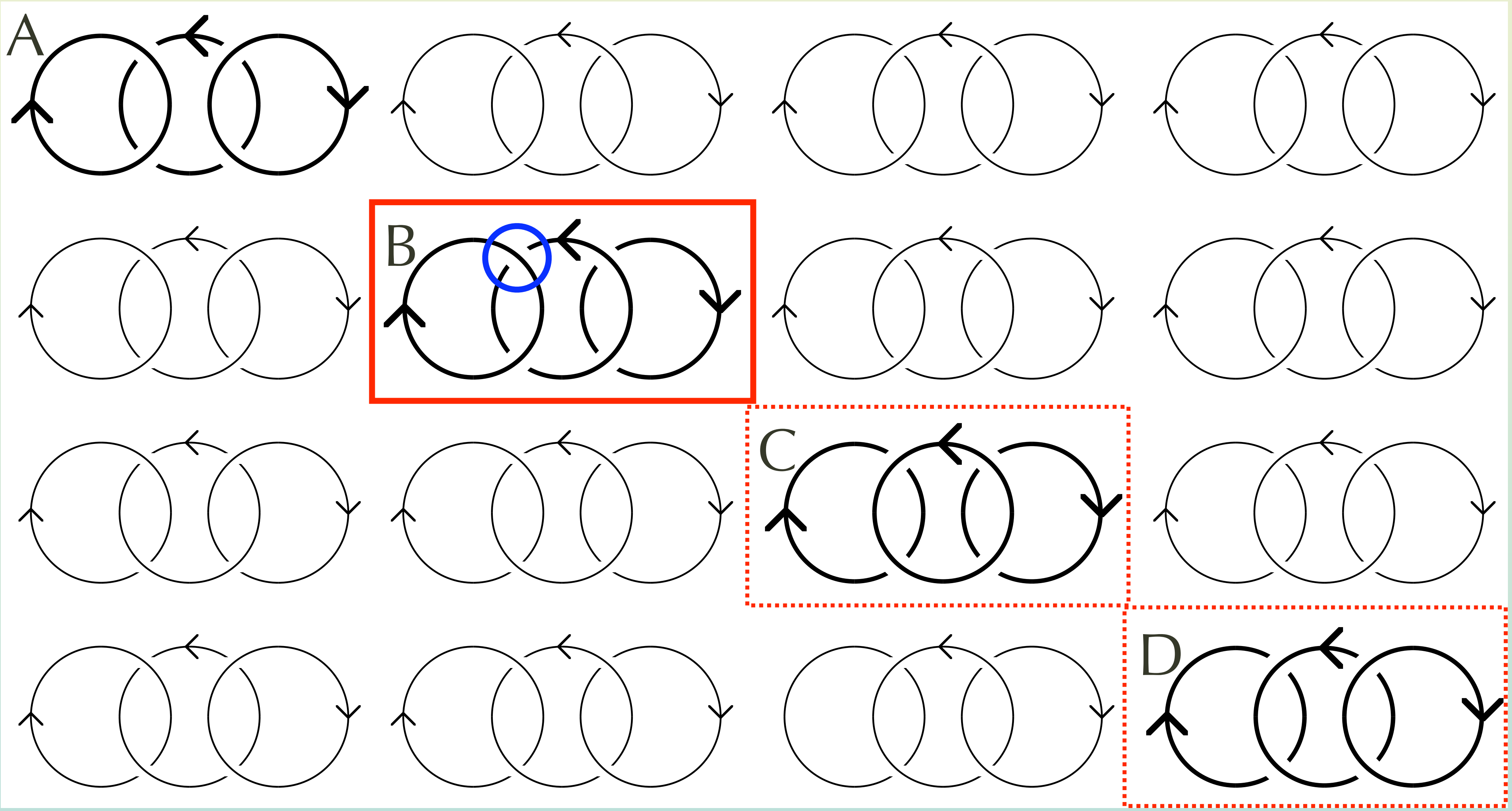
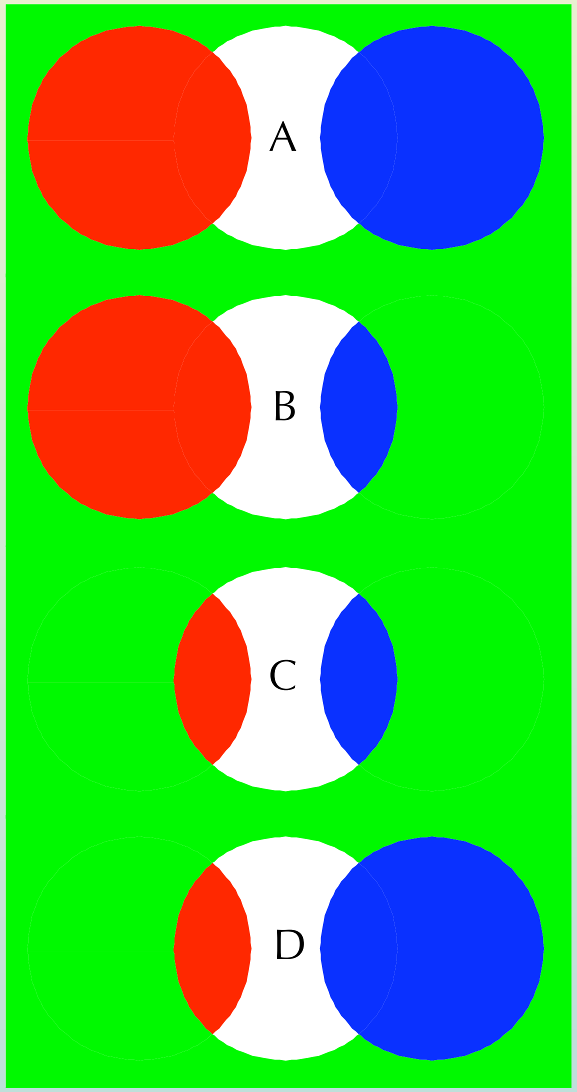
Minimum-Difference Search

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

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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.

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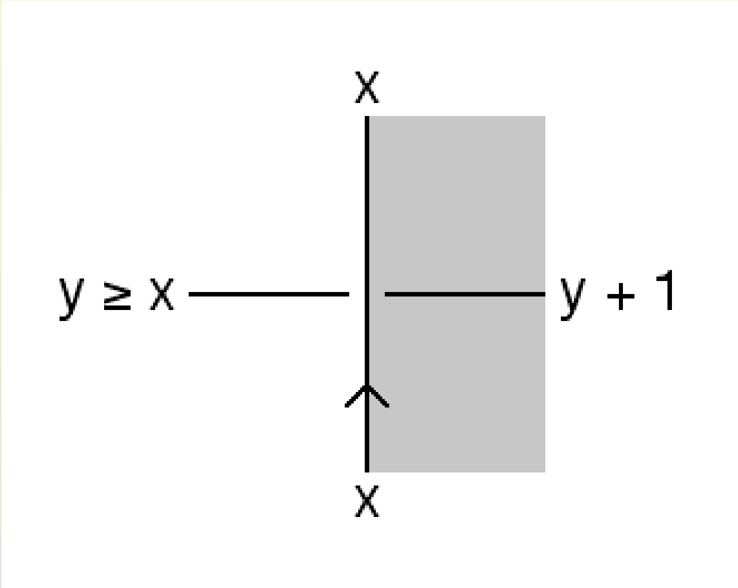
Constraint Propagation (Waltz '75)

- 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.

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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***.

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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

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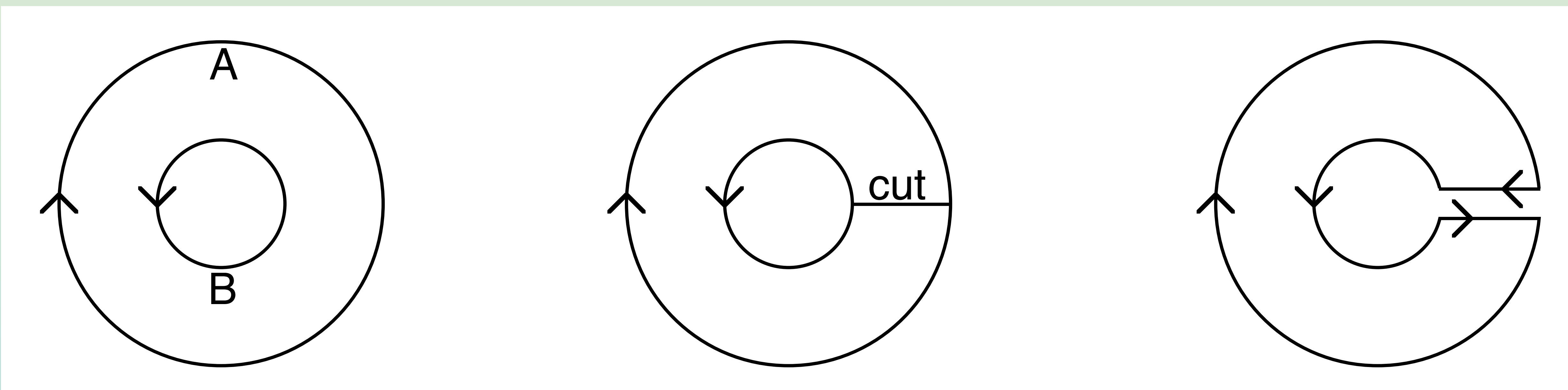
Boundary Grouping with Cuts

- 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.

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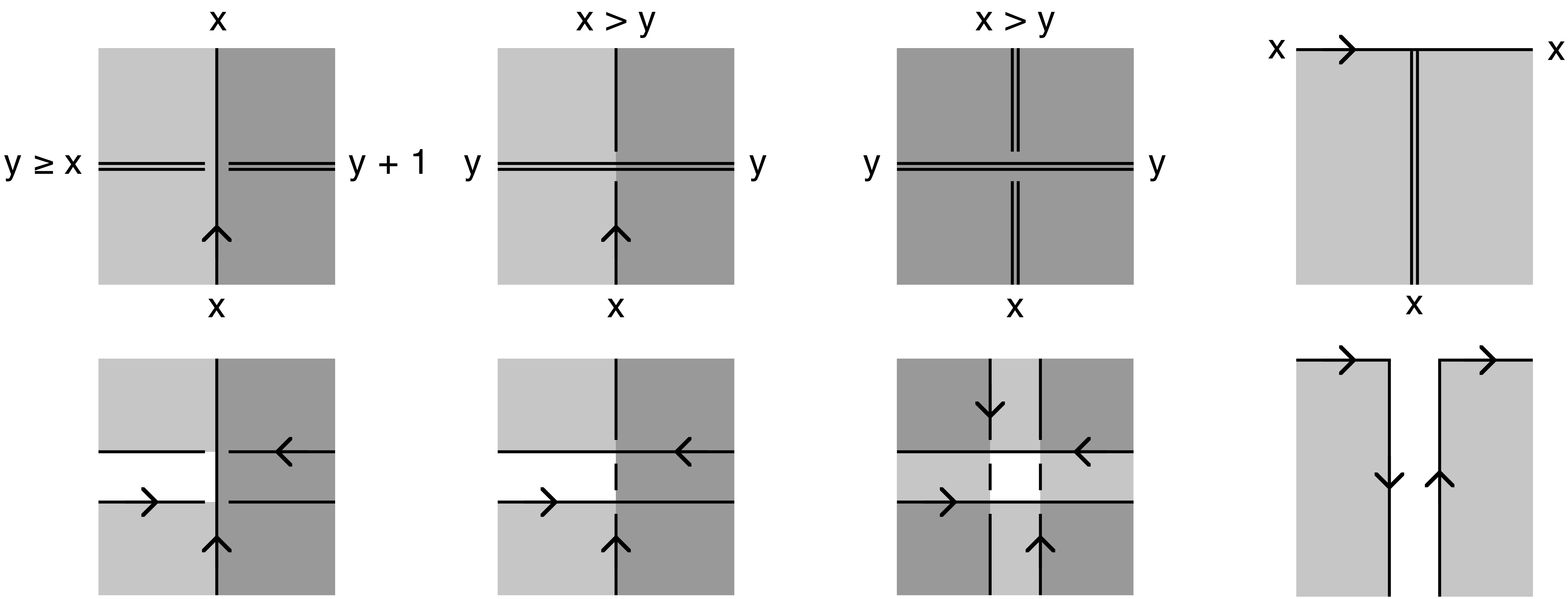
Cut Labeling Schemes

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)

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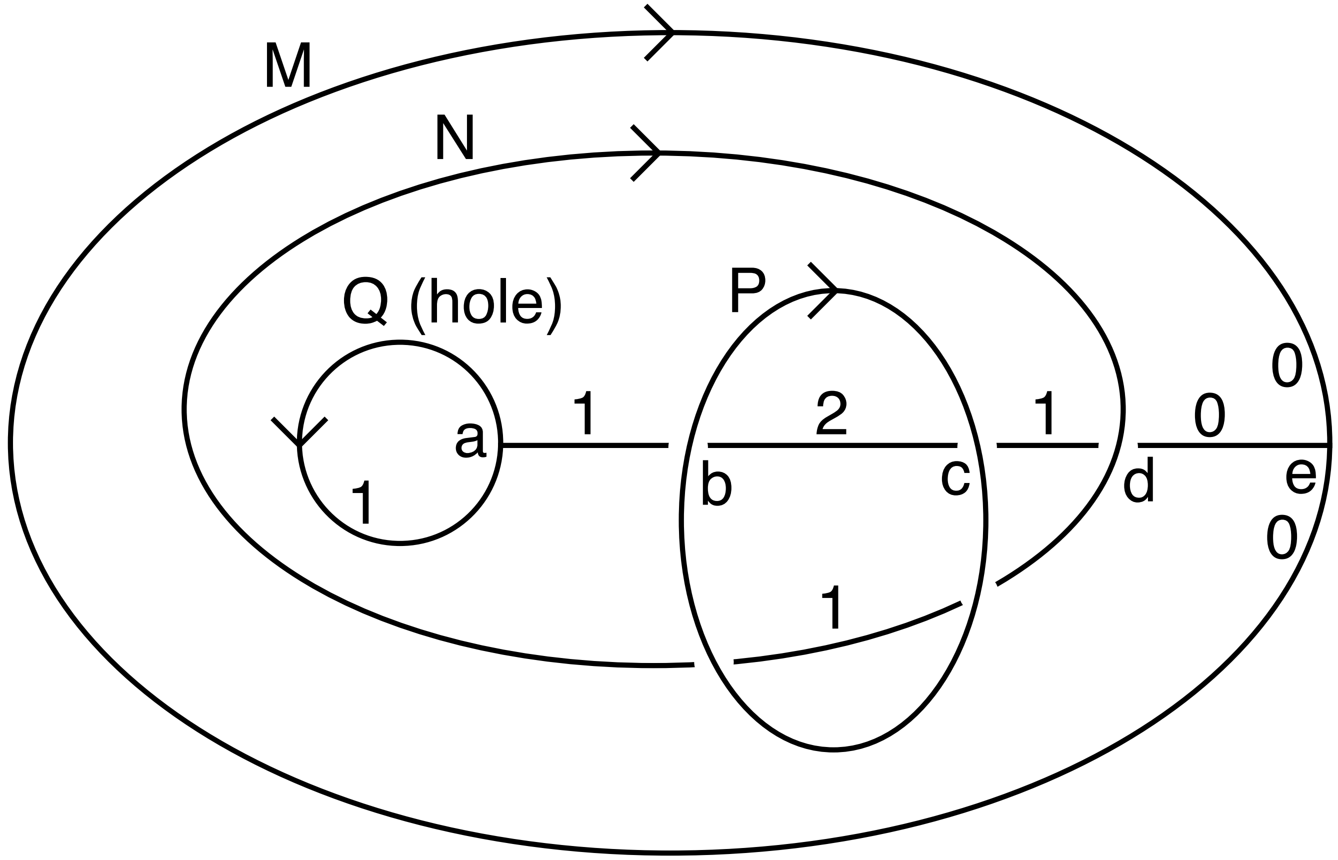
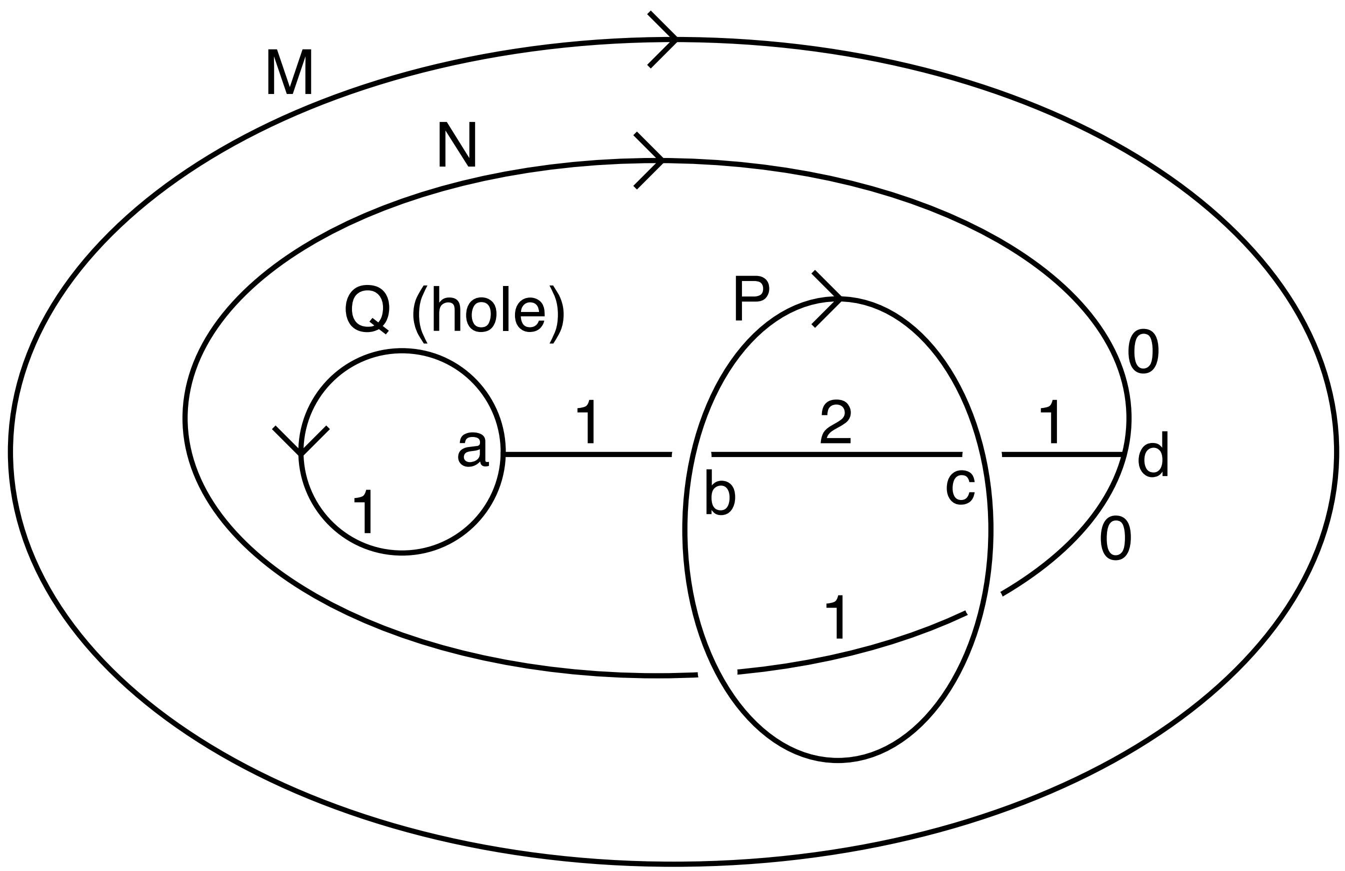
Finding Legal Cuts



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



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

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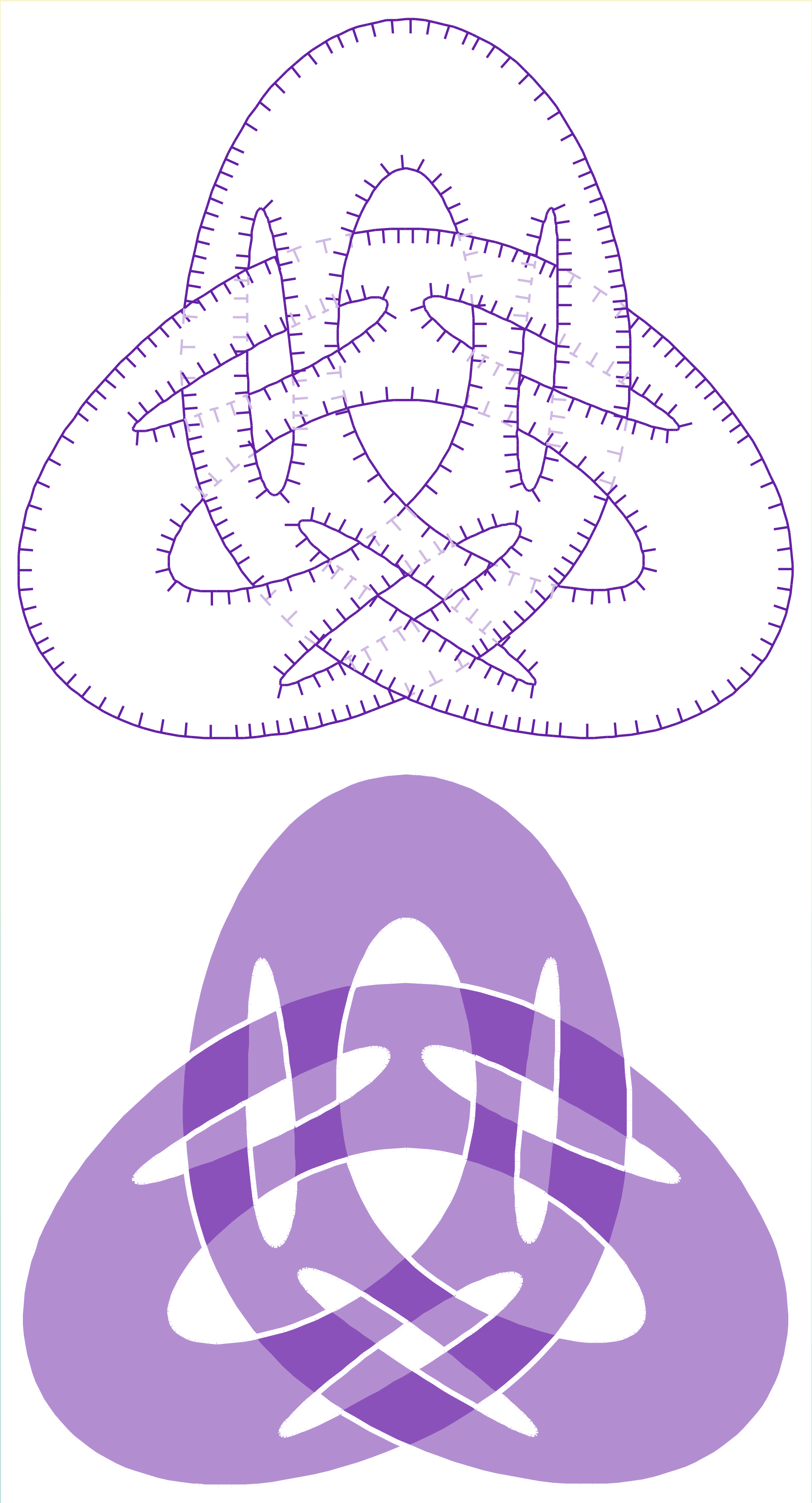
Rendering

- 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.

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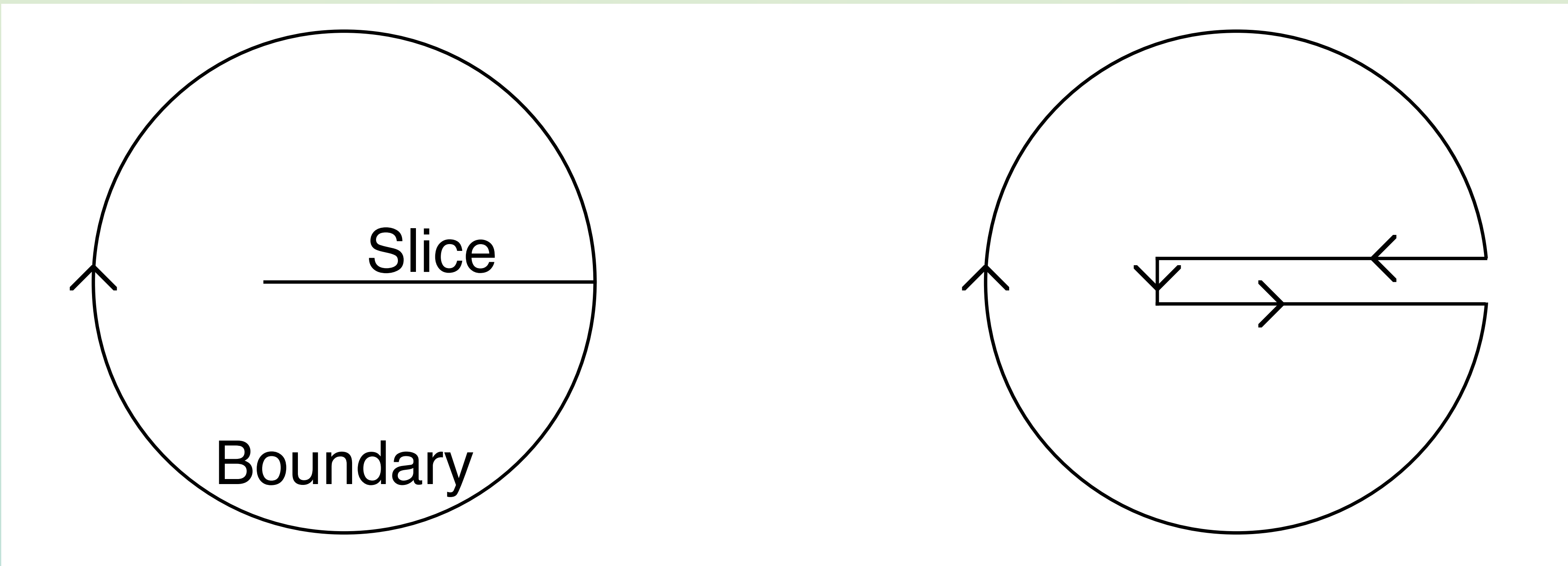
Slice

- 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.

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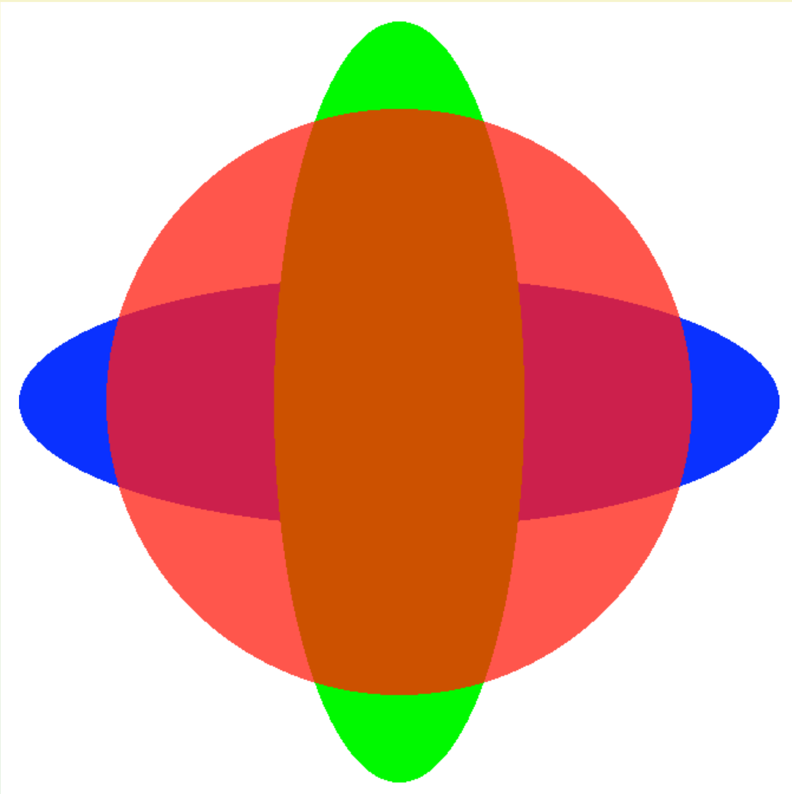
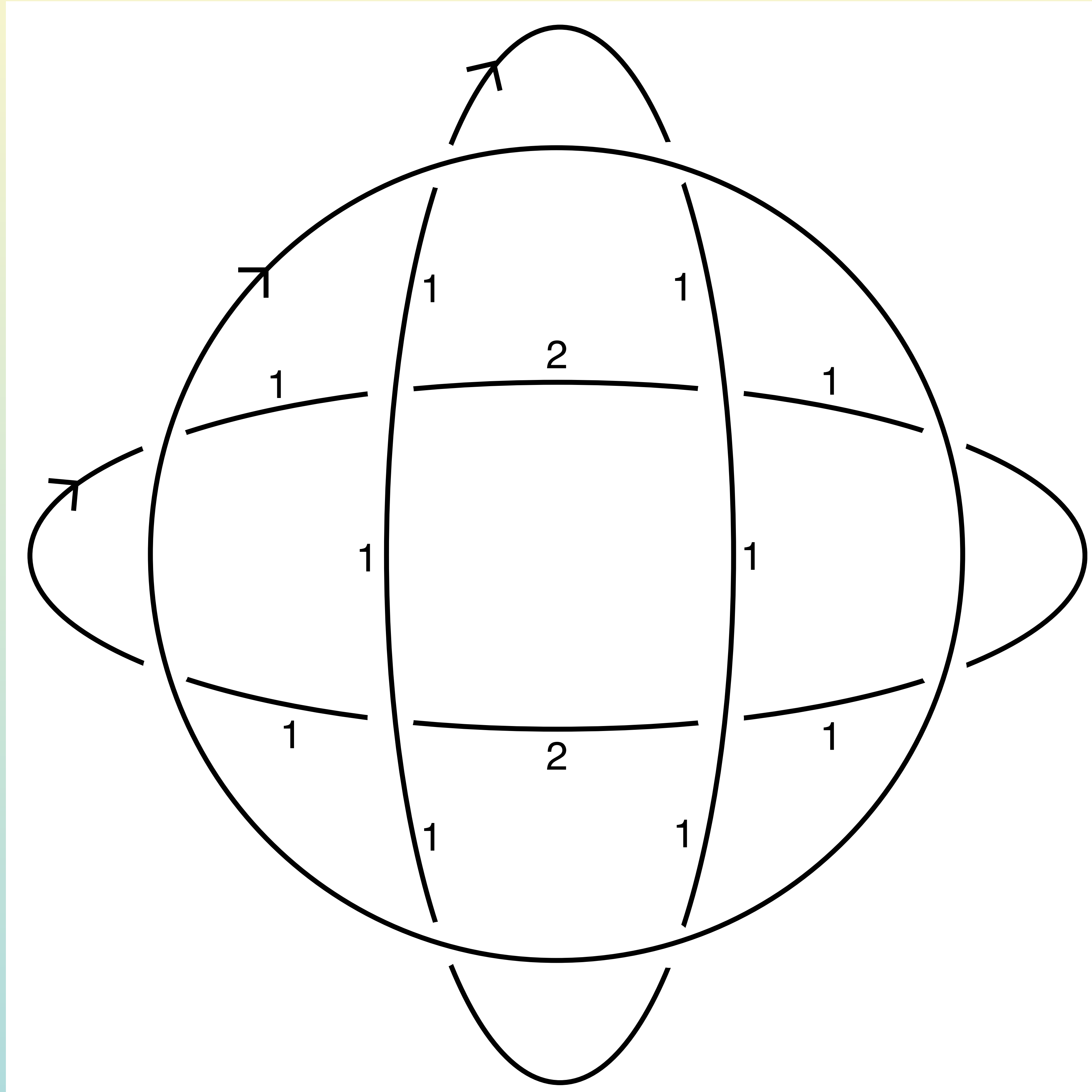
Using Slices to Find Region Coverings





Red is above **green**, which is above blue.

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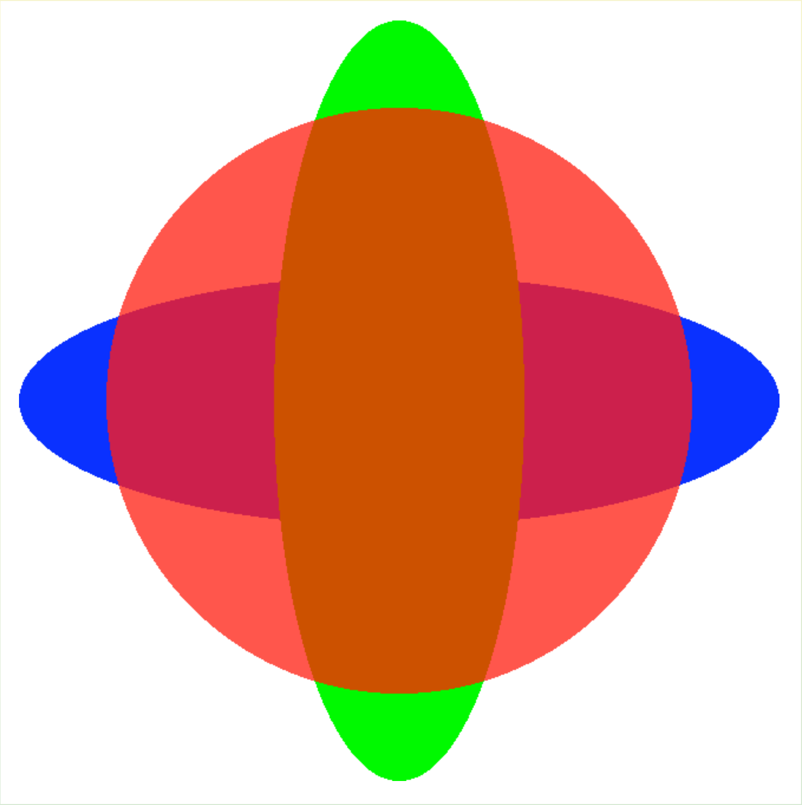
Using Slices to Find Region Coverings



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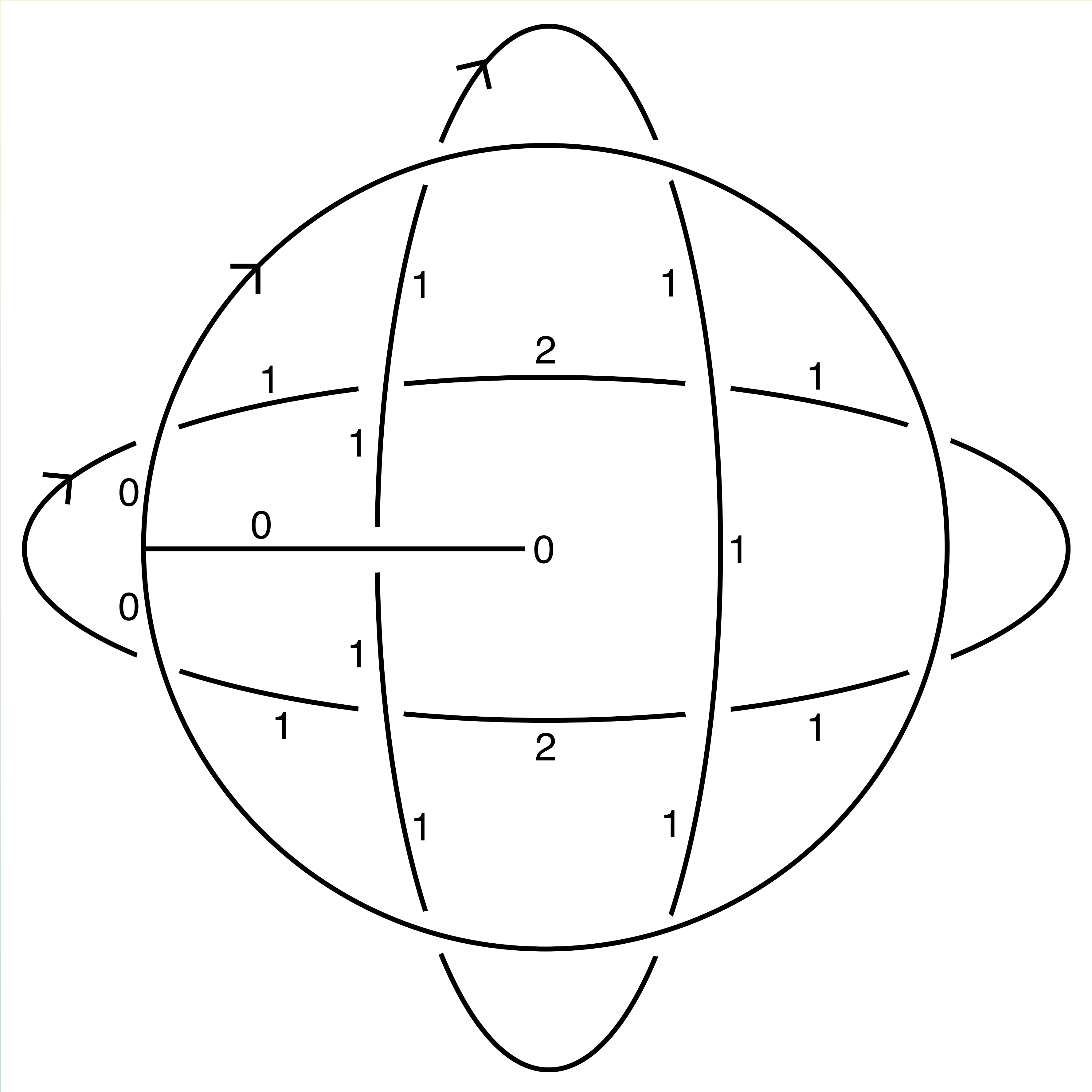

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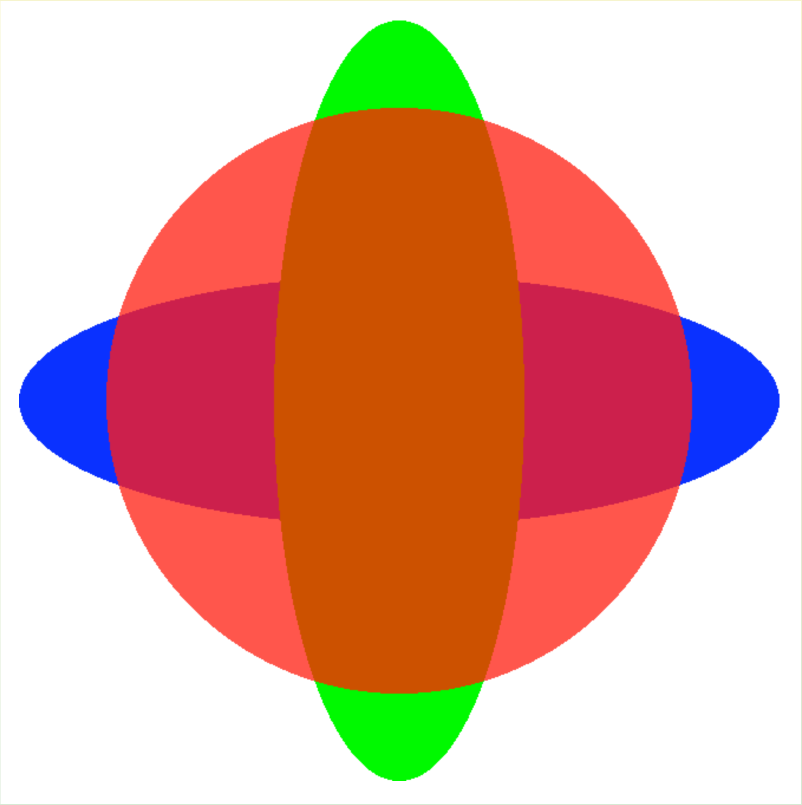

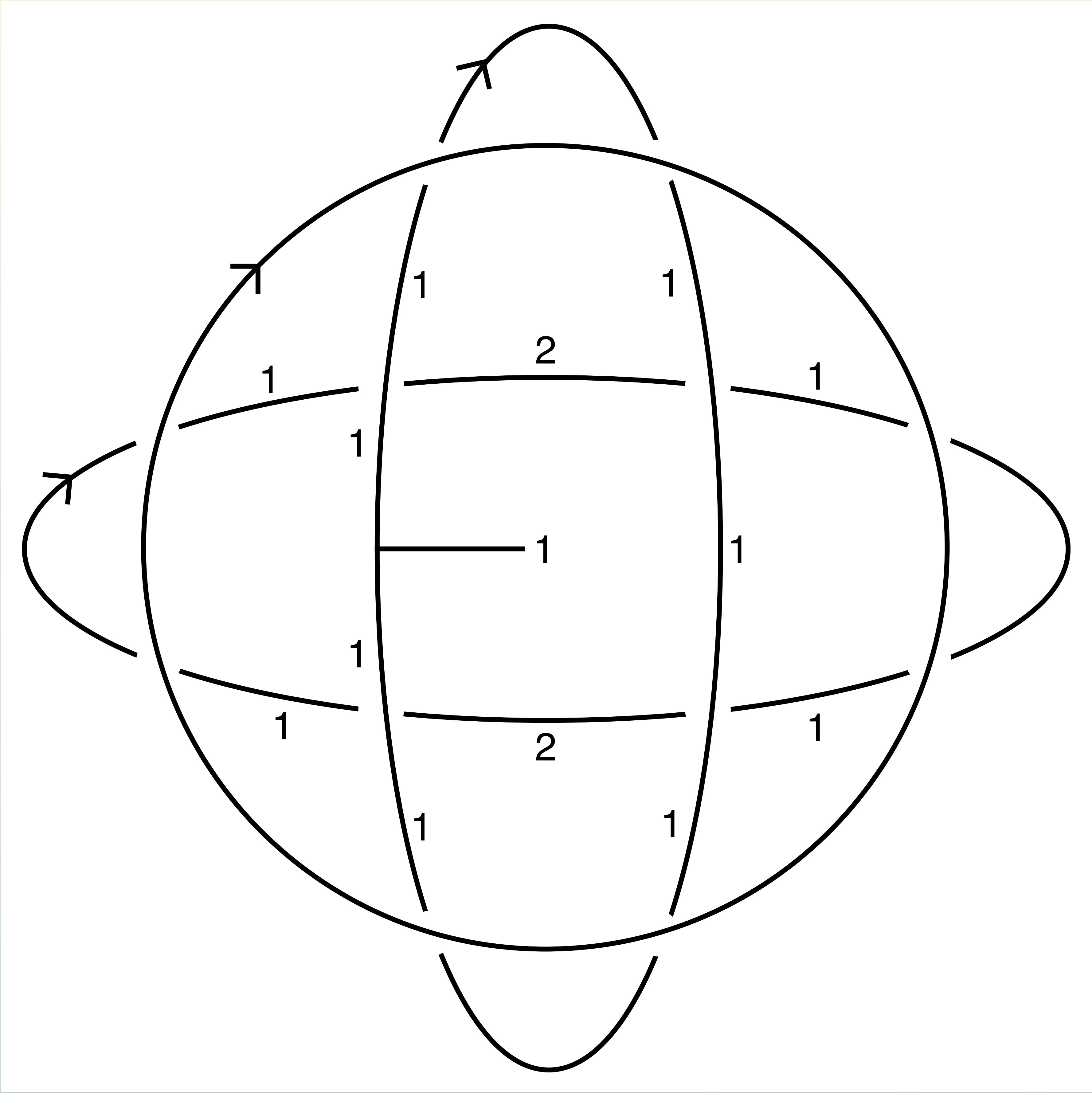

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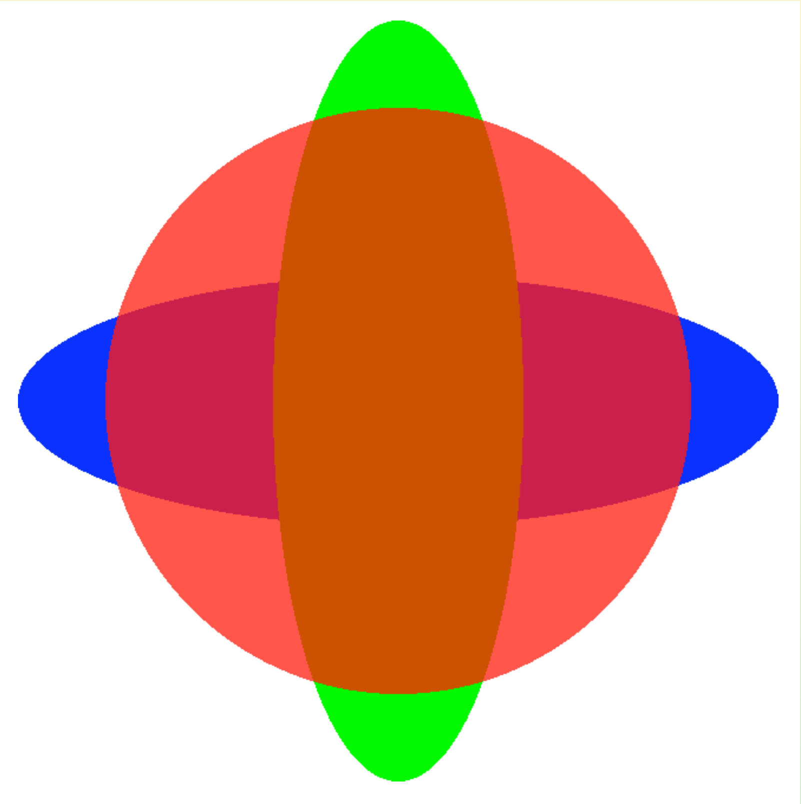

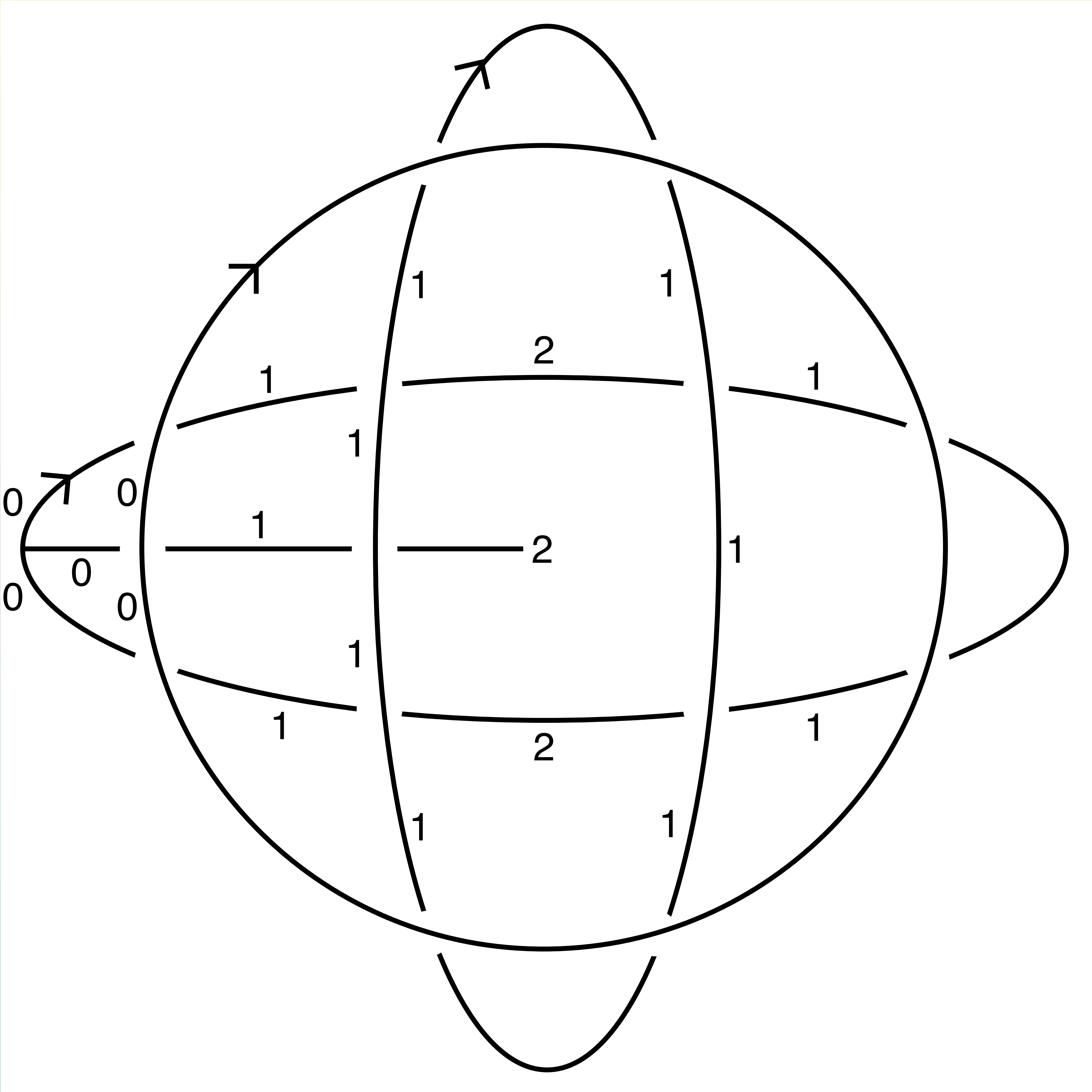

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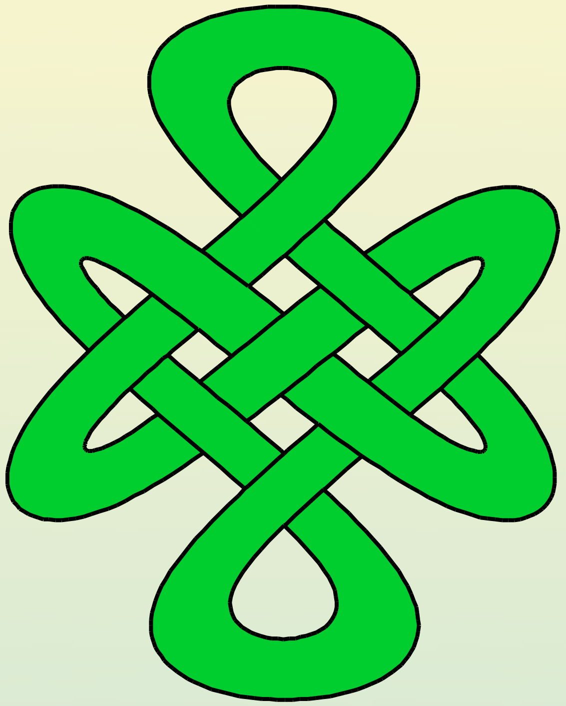
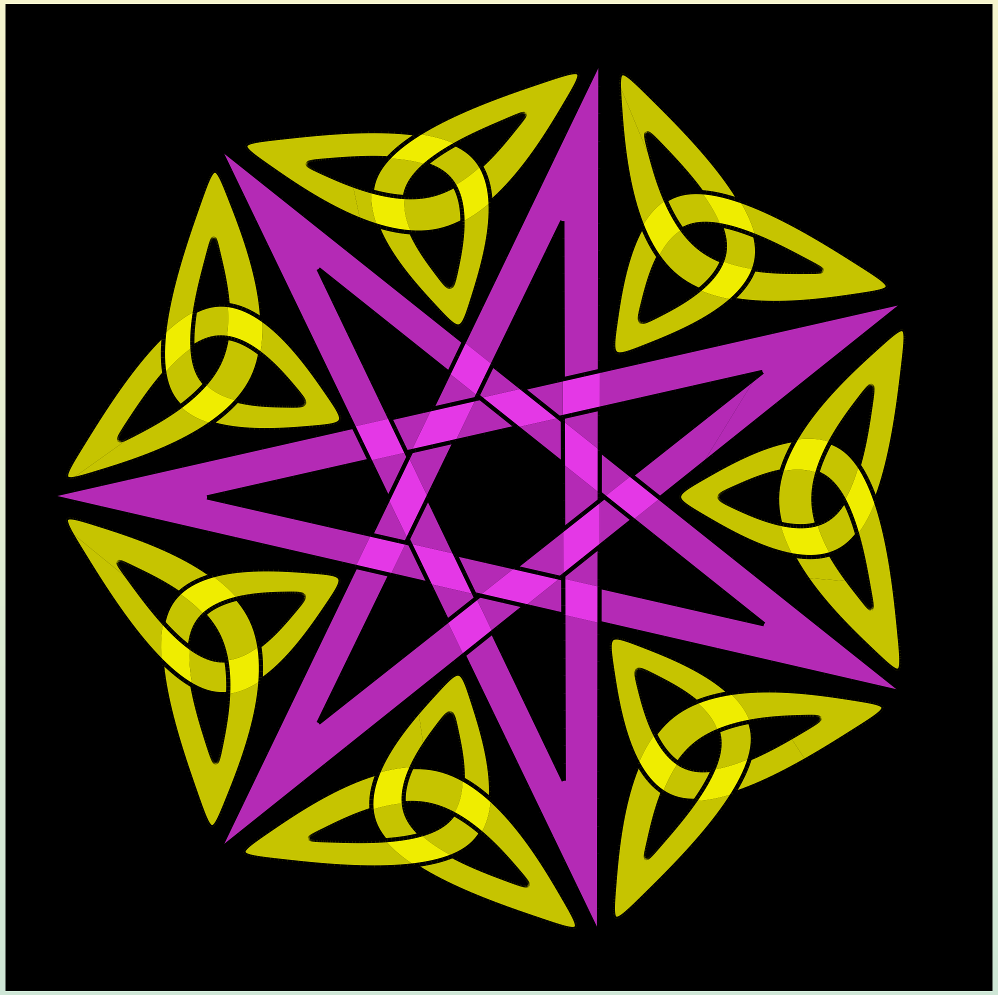
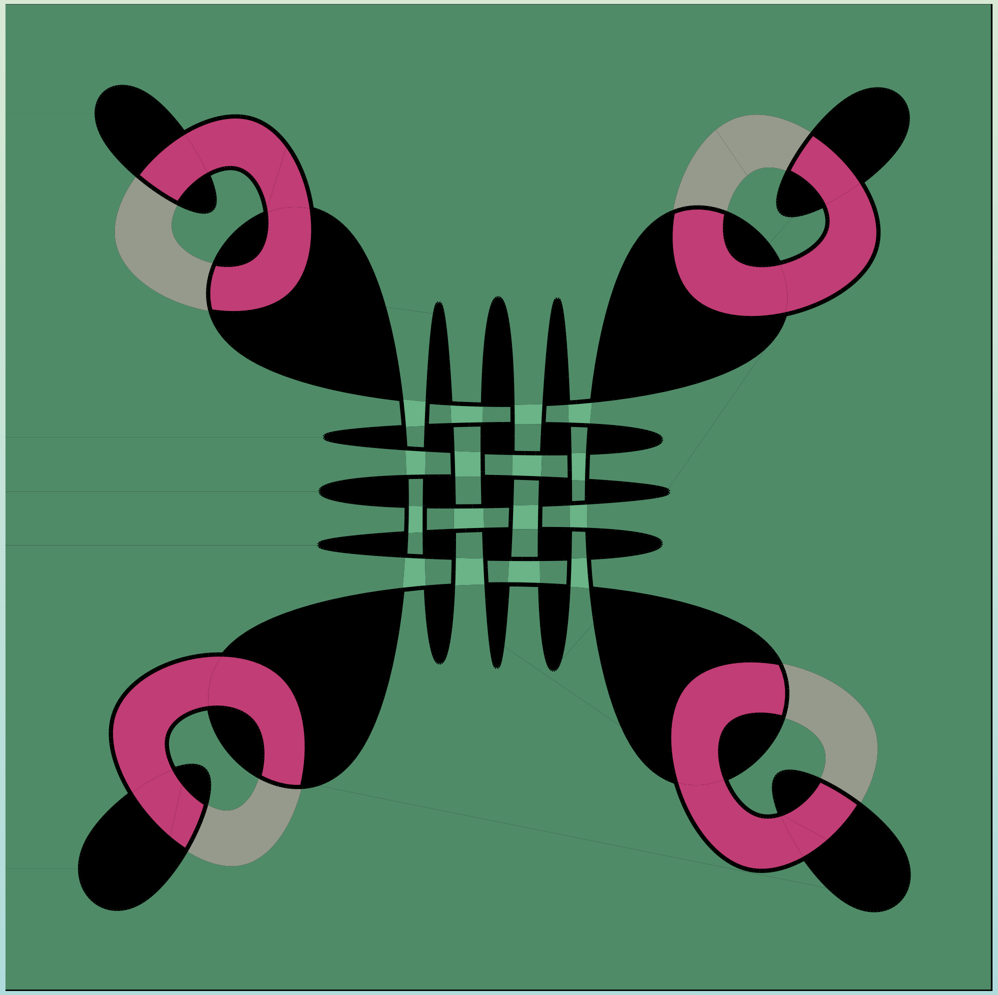
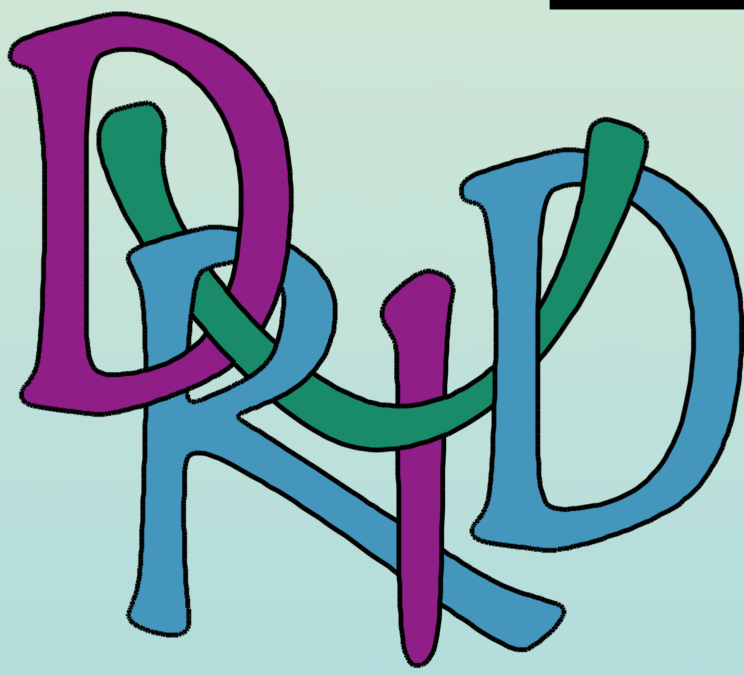
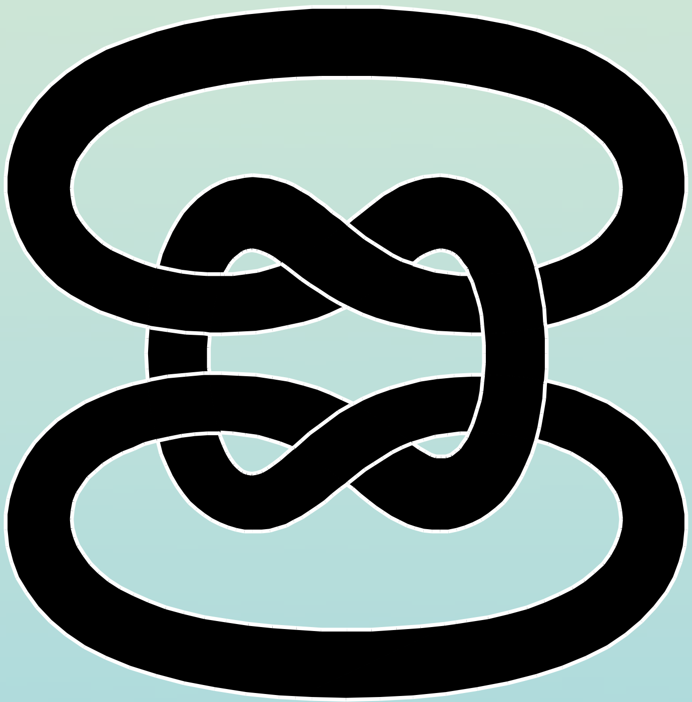
Druid Examples











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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.

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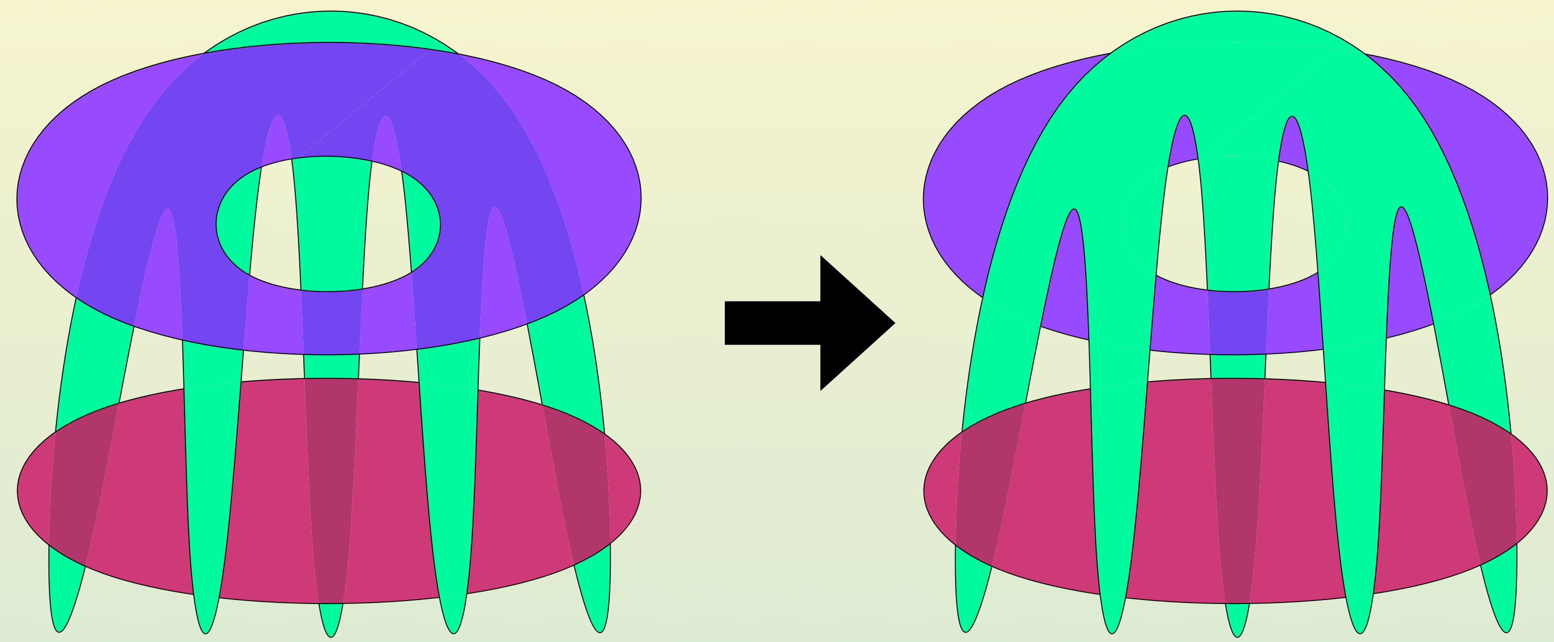
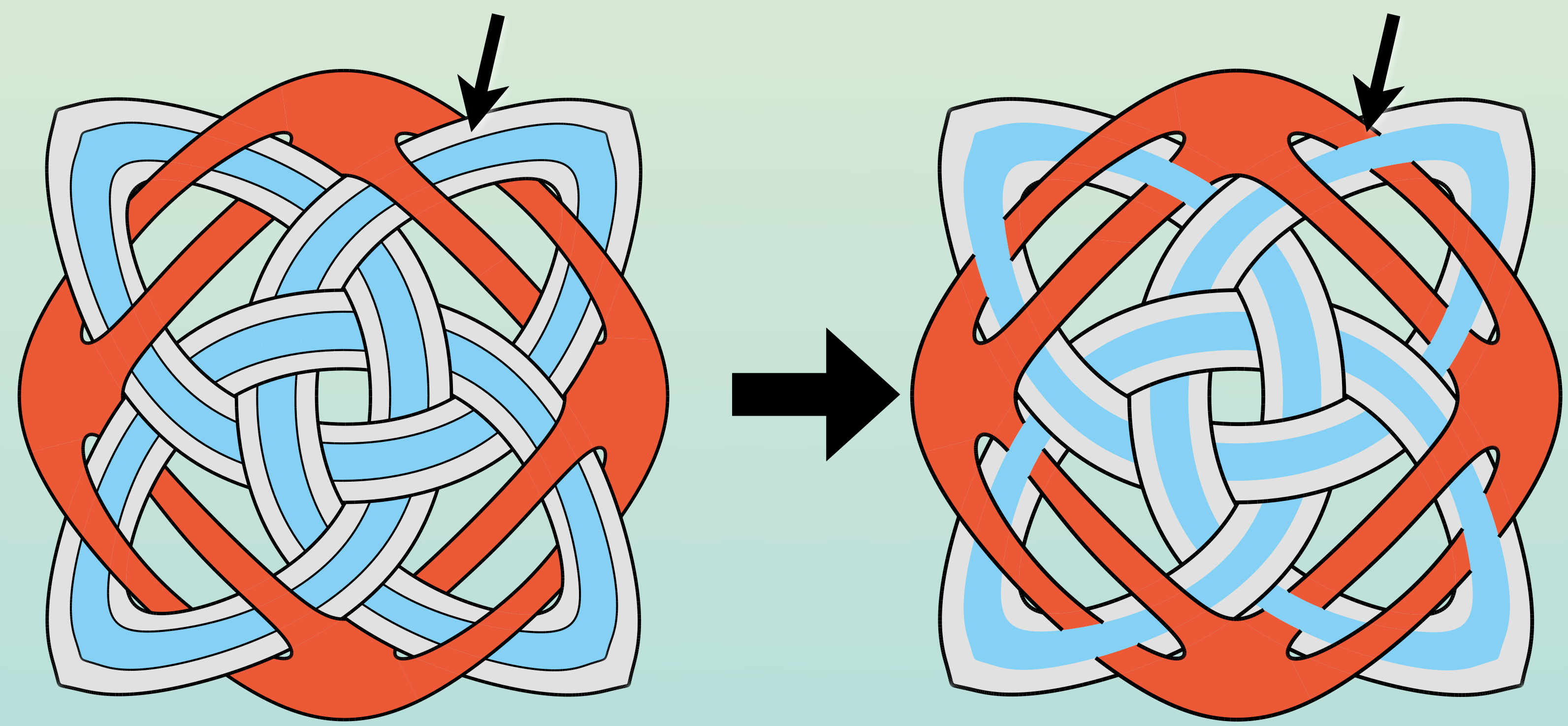
A Problem with the Search (contd.)

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)



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Crossing-State Equivalence Class Rule

- Discovered a property of 2½D scenes, the ***crossing-state equivalence class (CSEC) rule***.

- Use this property to improve performance.

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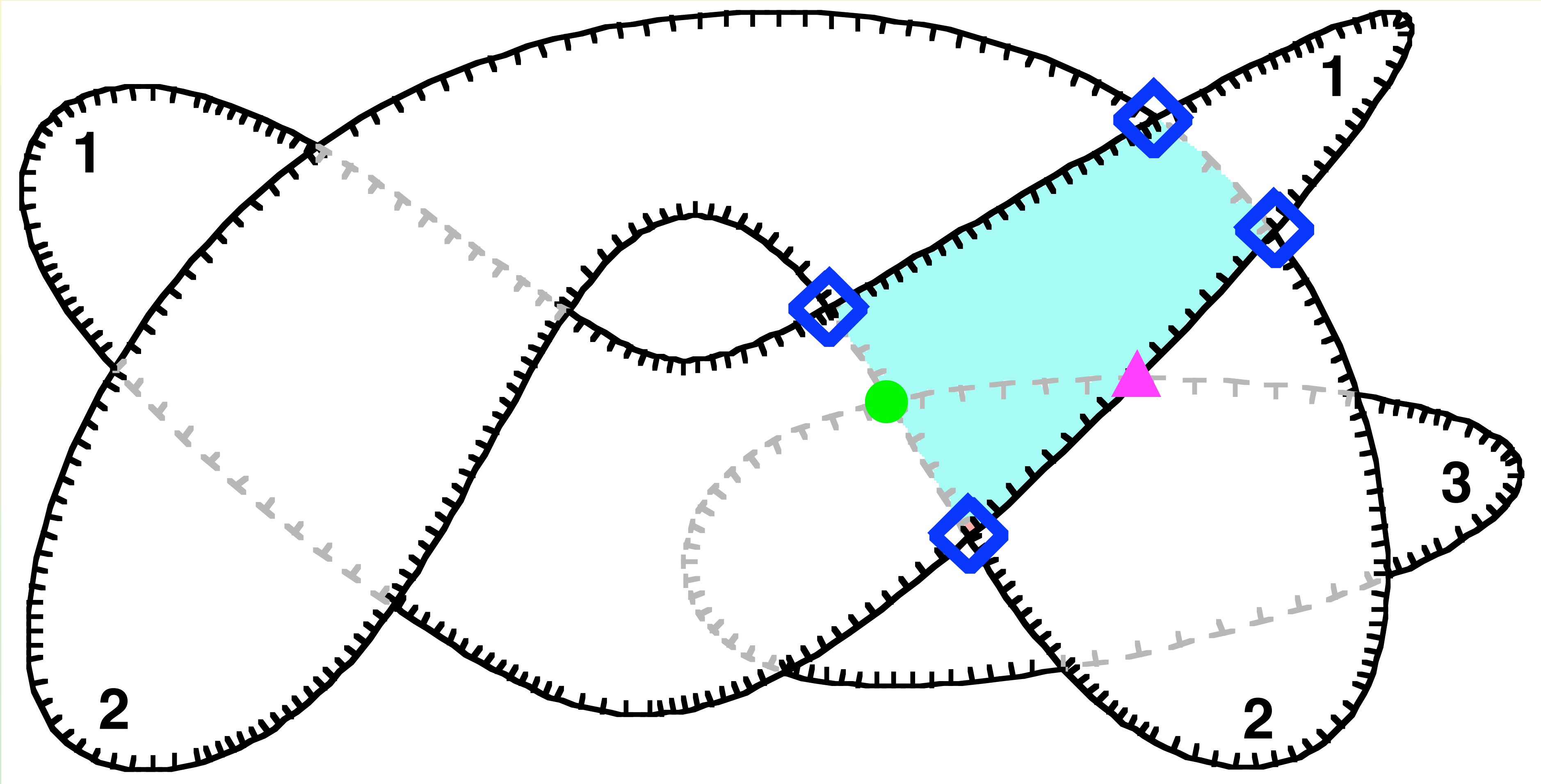
Area of Overlap

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

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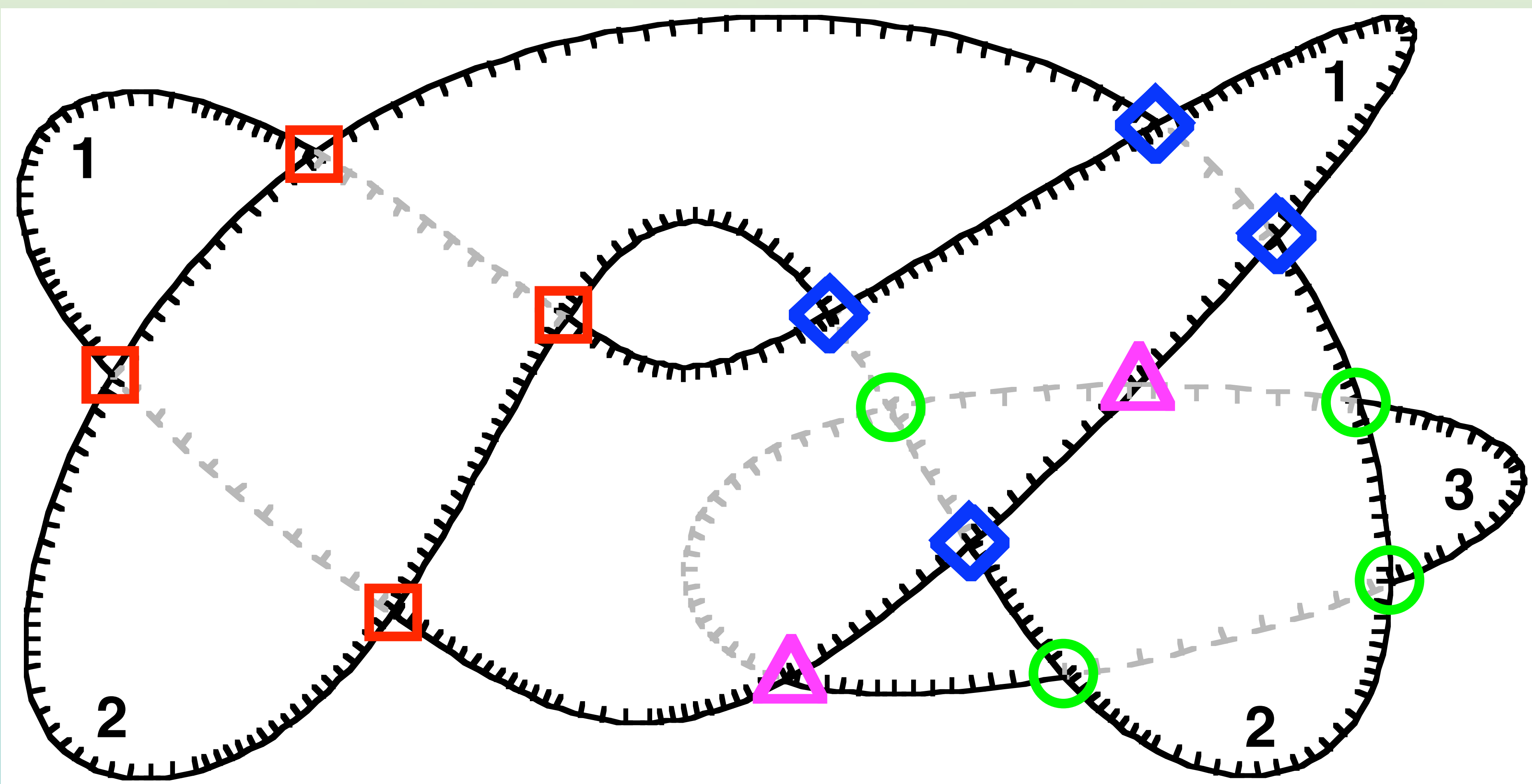
Crossing-State Equivalence Class (CSEC)

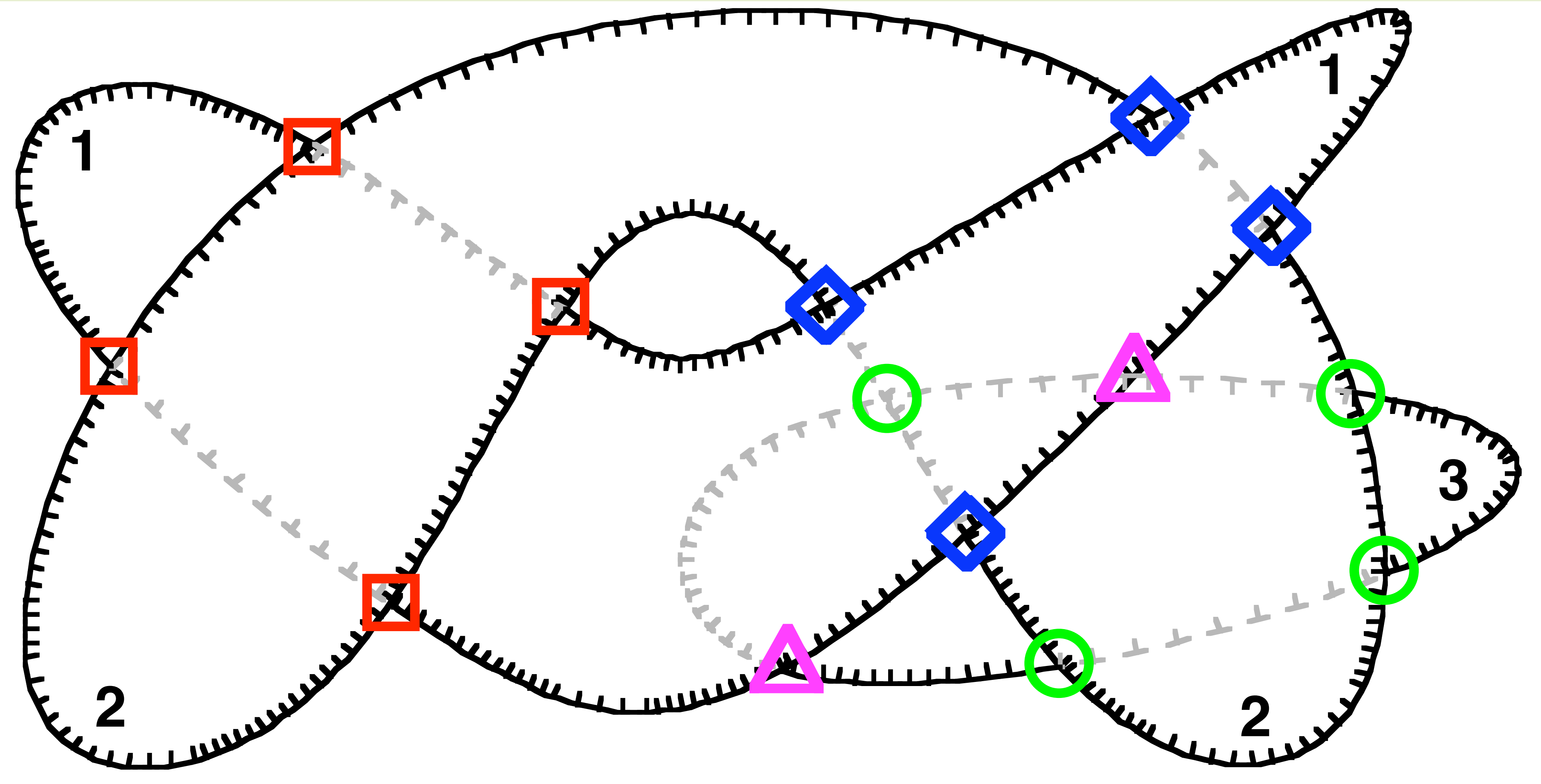
The *corners* of an *area-of-overlap* comprise a *CSEC*.



Unique shapes/colors indicate CSECs

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*.

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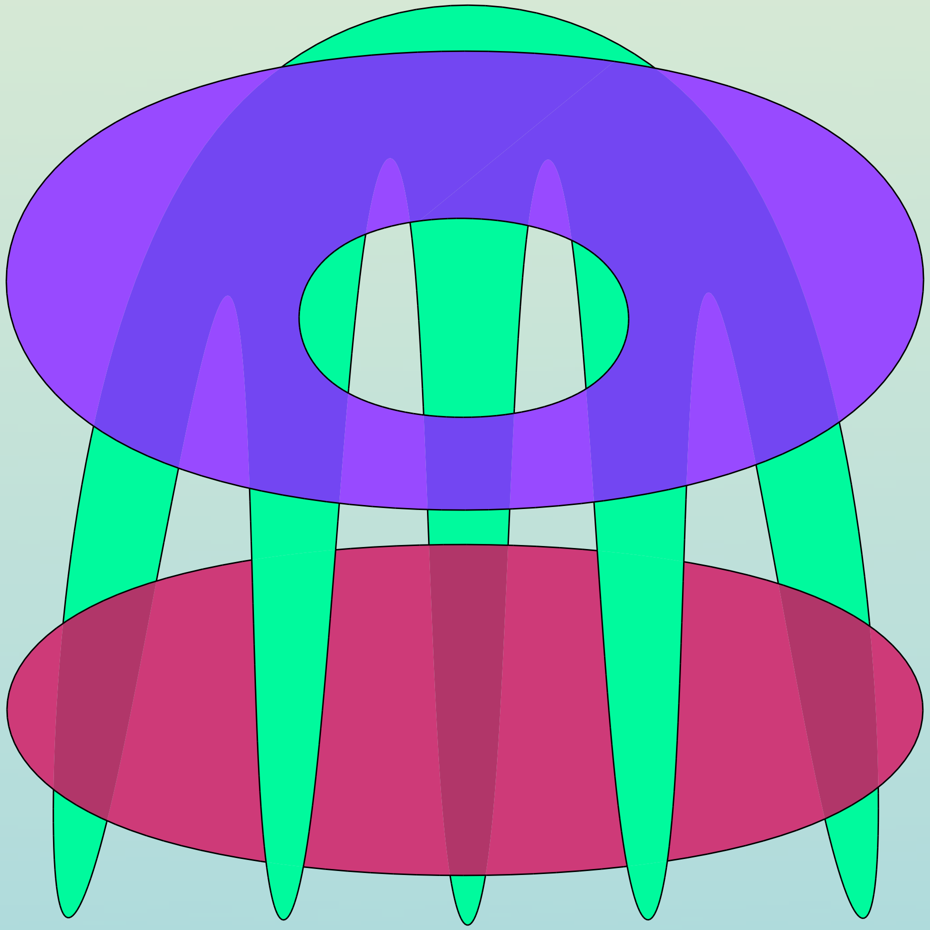
Labeling with CSECs

- 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	Labeling space size
No	2^{40} (for 40 crossings)
Yes	2^{7} (for 7 CSECs)

Relabeling with CSECs

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

    - ***Labeling*** and ***relabeling*** both perform a tree search of size 2^C (C = num crossings).

2. *Druid (NEW)*: (Wiley and Williams '06b)

    - ***Relabeling*** performed by maintaining the CSECs ***without a search***. Segment depth changes are directly deduced.

    - ***Labeling*** searches a space of size 2^E (E = num CSECs).

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.

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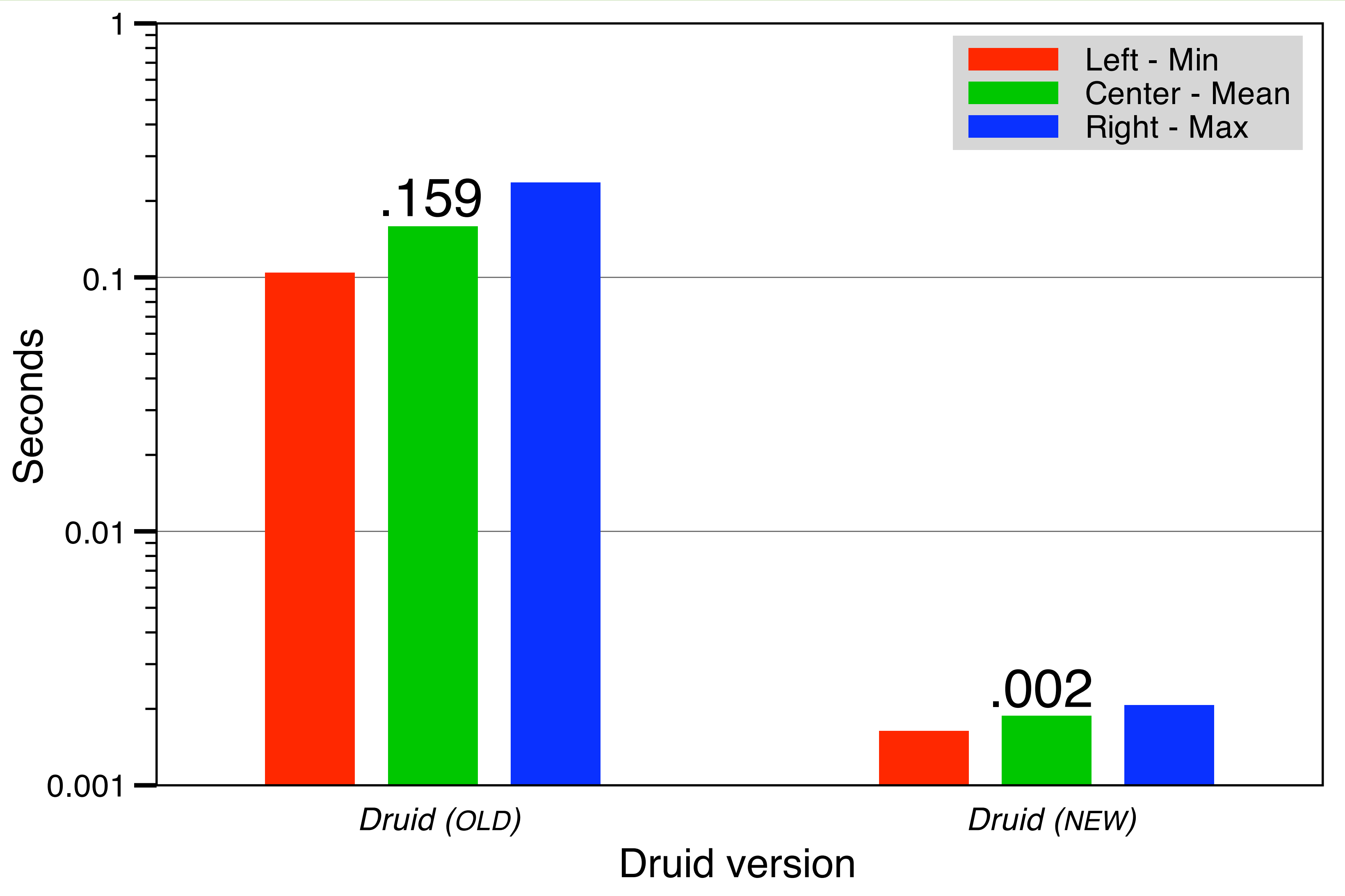
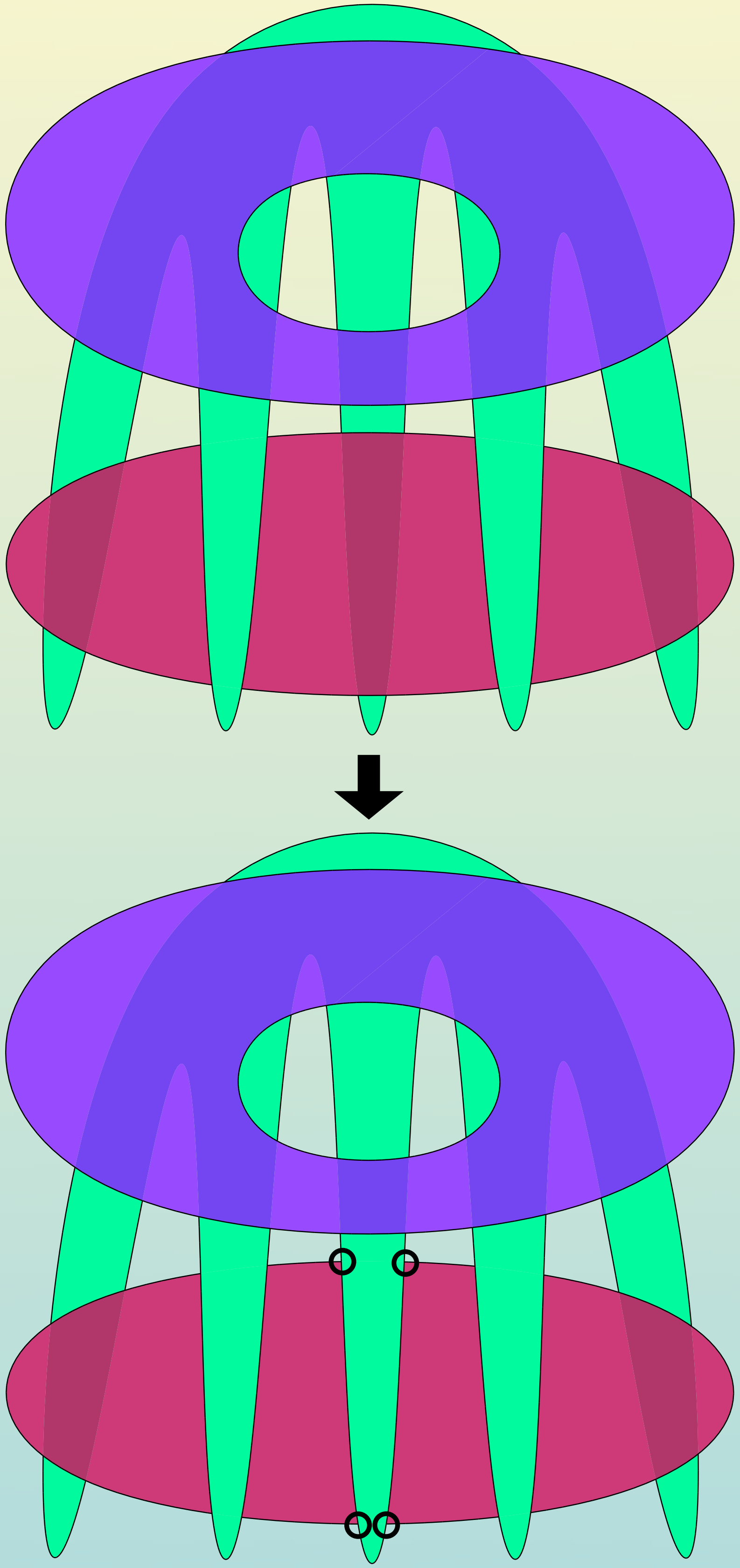
Relabeling Results: A Small CSEC Flip

- Size 4, indicated with circles
- Running times on 1.6GHz G5 PowerMac
- *Druid* (NEW) performs ~100 times faster than *Druid* (OLD)





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

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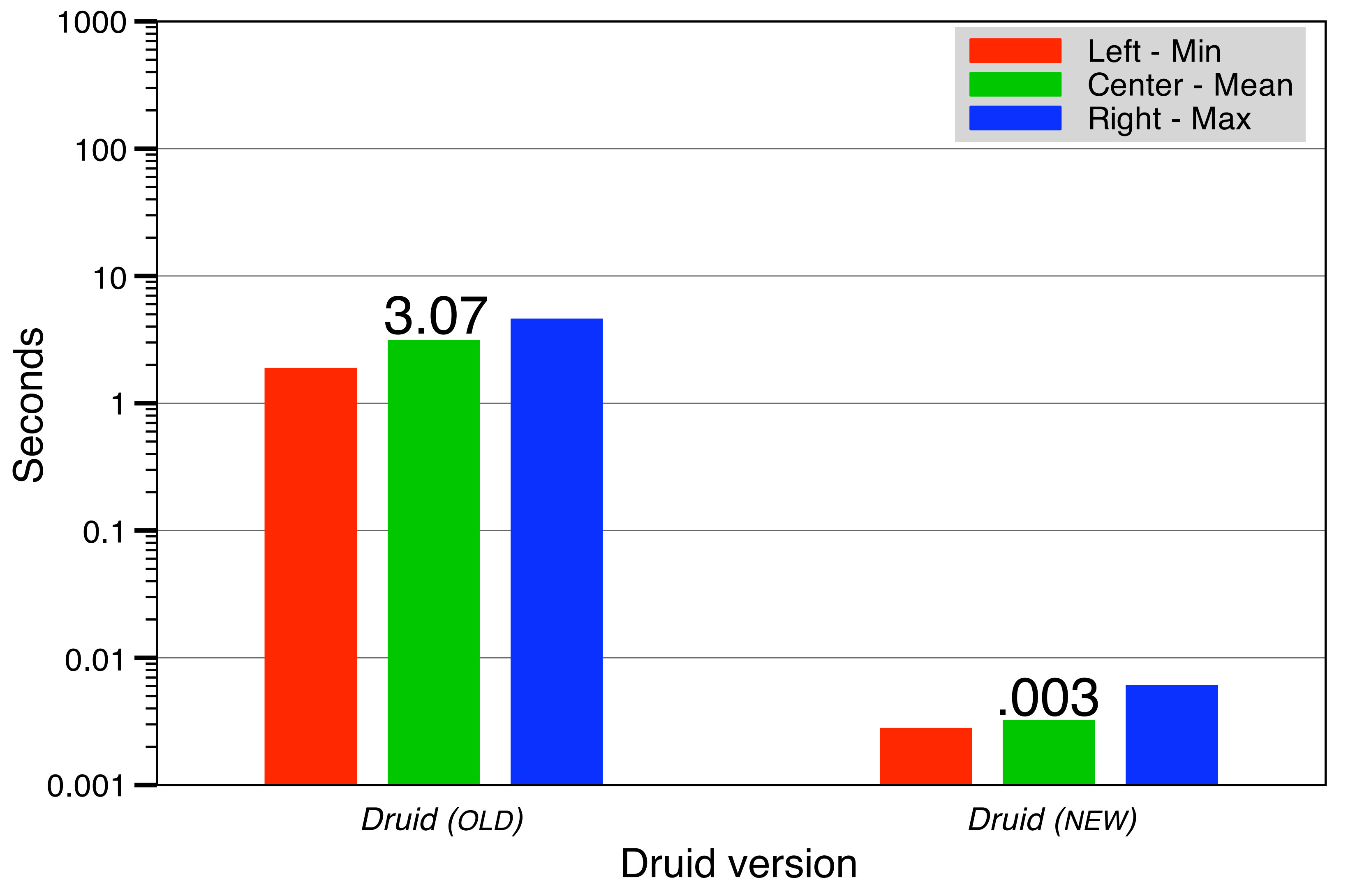
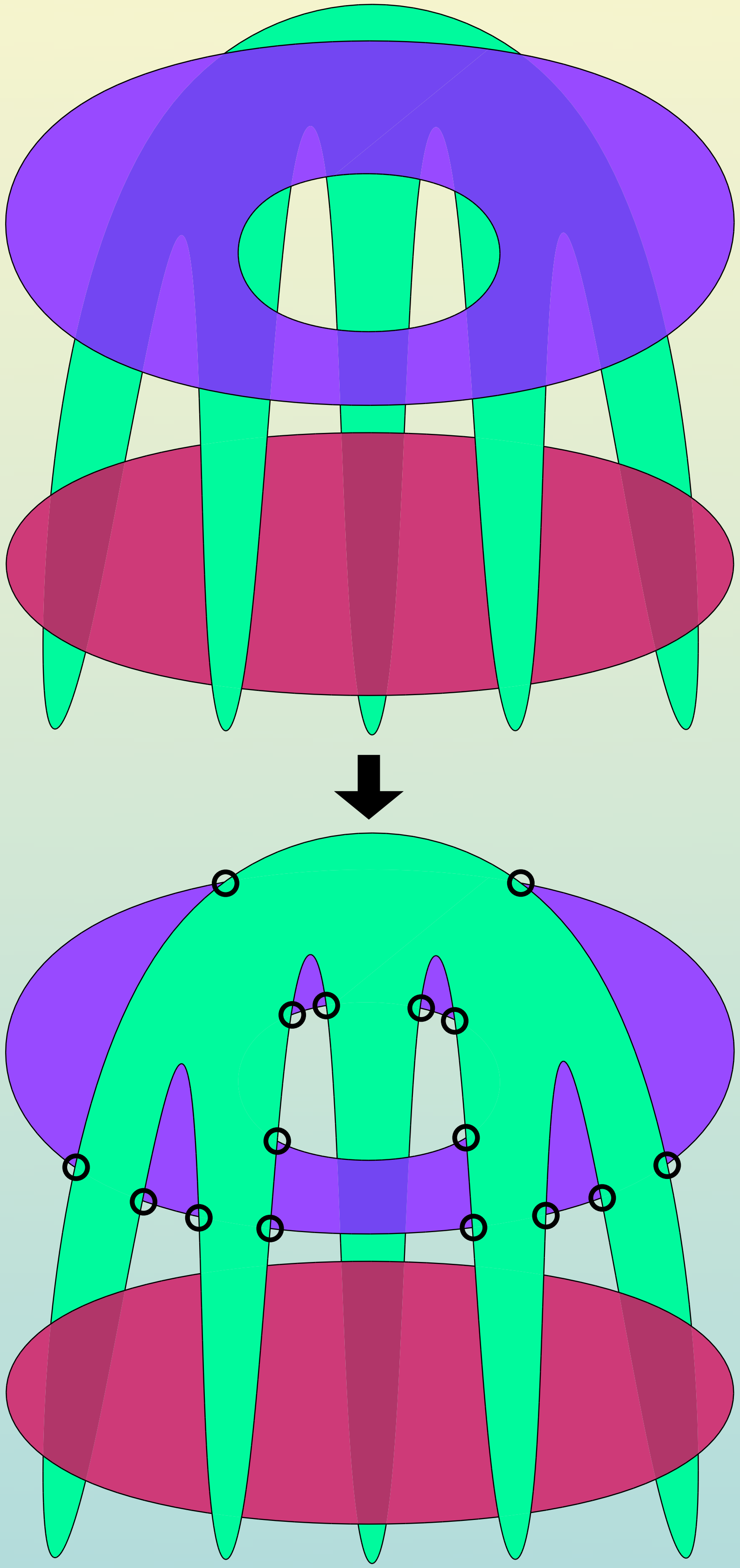
Relabeling Results: A Large CSEC Flip

- Size 16, indicated with circles
- *Druid* (OLD) cannot relabel in a reasonable time.
- *Druid* (NEW) performs ~1000 times faster.
- Note: *Druid* (OLD) failed 50% of the time.





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

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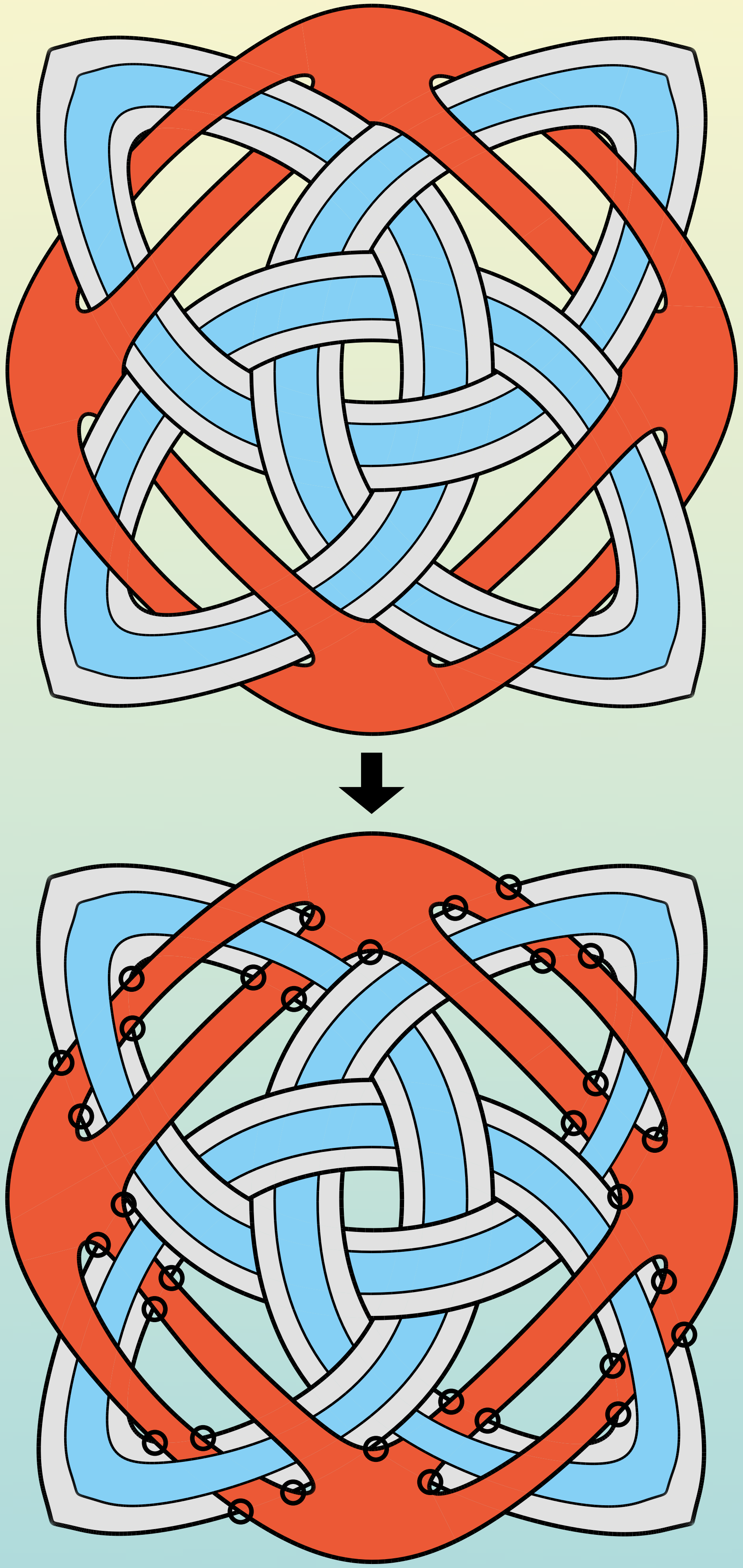
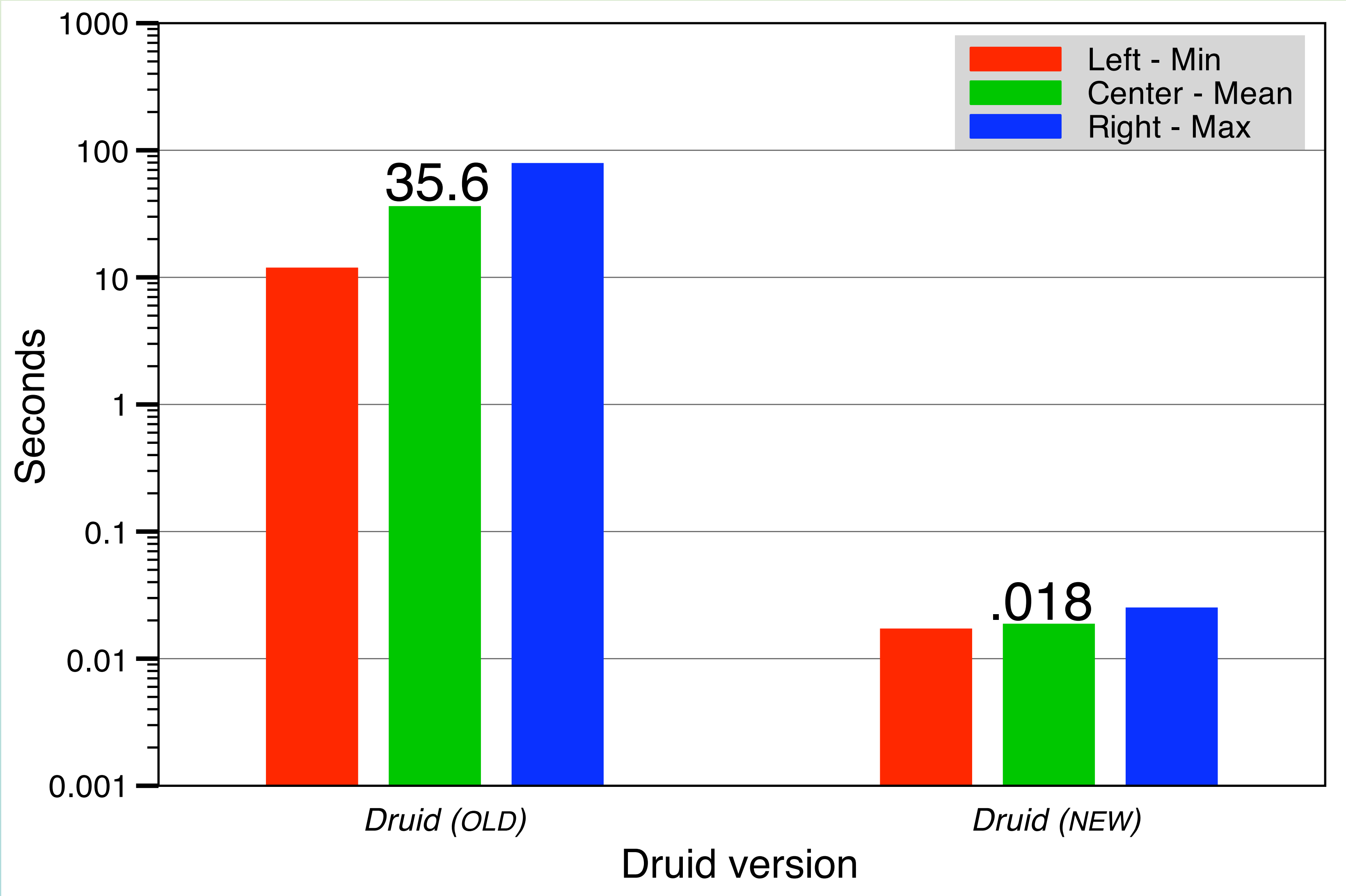
Relabeling Results: A Complex Figure



- 256 crossings, 64 CSECs
- *Druid* (OLD) cannot relabel this small CSEC flip in a reasonable time.
- *Druid* (NEW) relabels in .02 seconds, ~2000 times faster.
- Note: *Druid* (OLD) failed 2% of the time.



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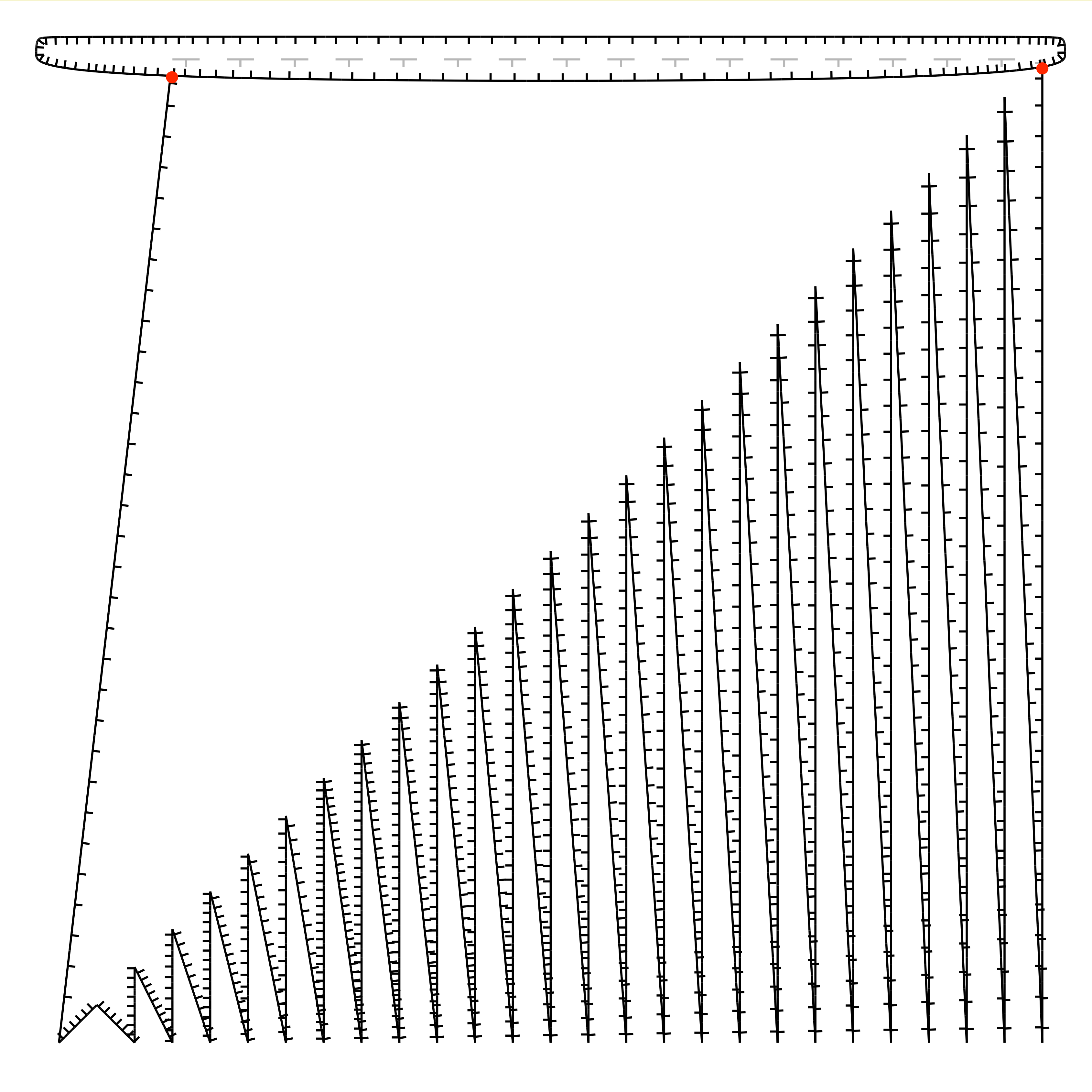
CSEC Flip Performance



Flipped CSEC size: linear in the total number of crossings

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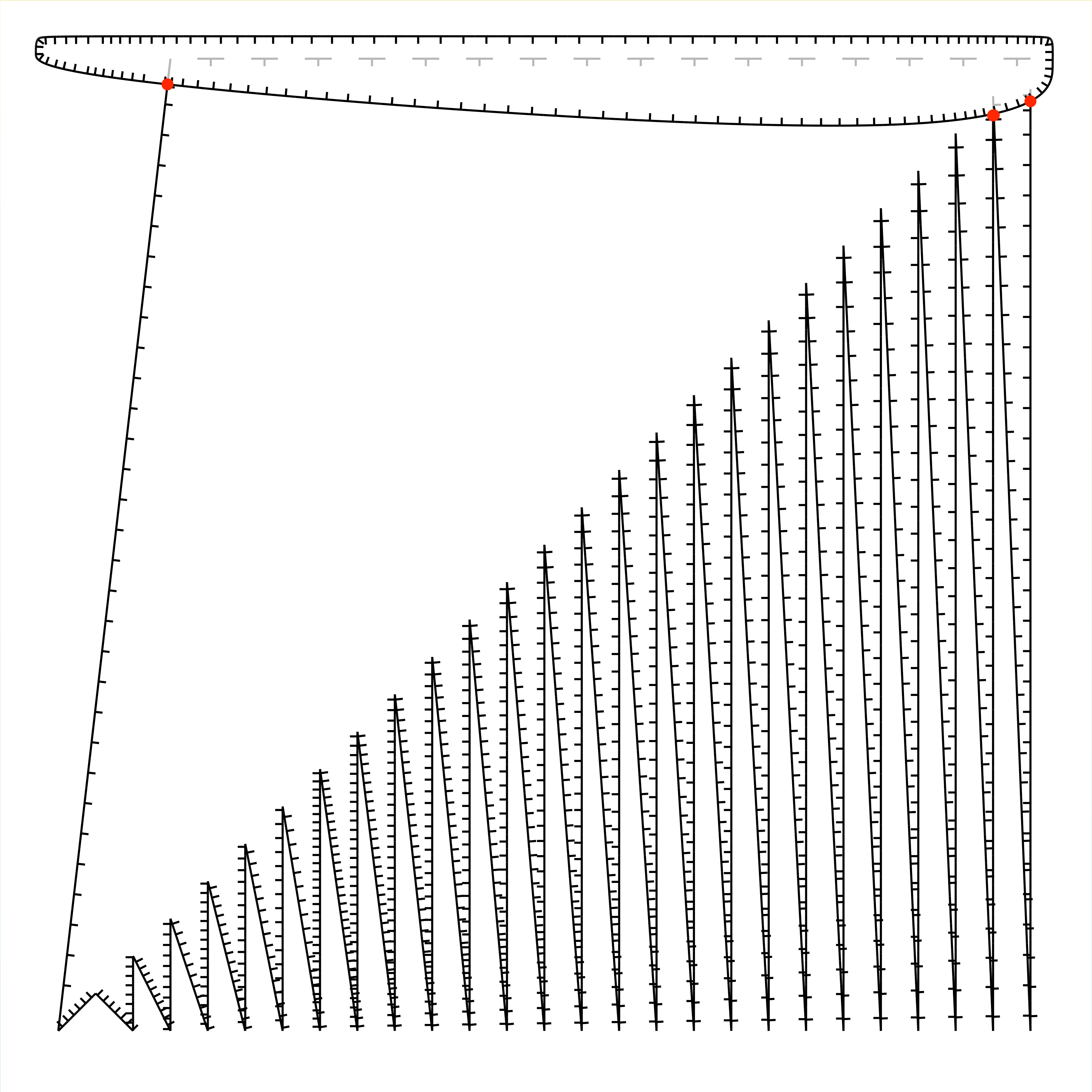
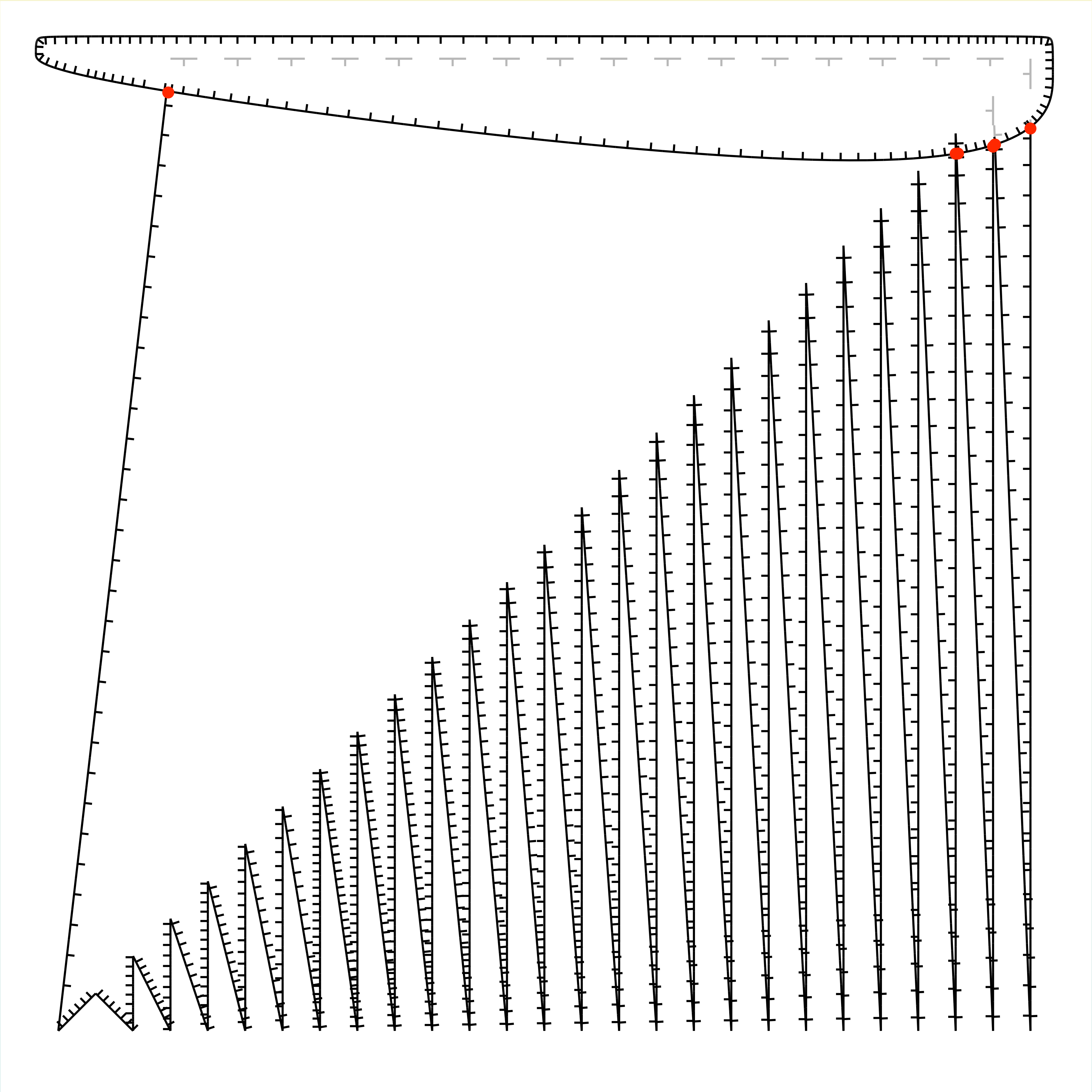
CSEC Flip Performance



Flipped CSEC size: linear in the total number of crossings

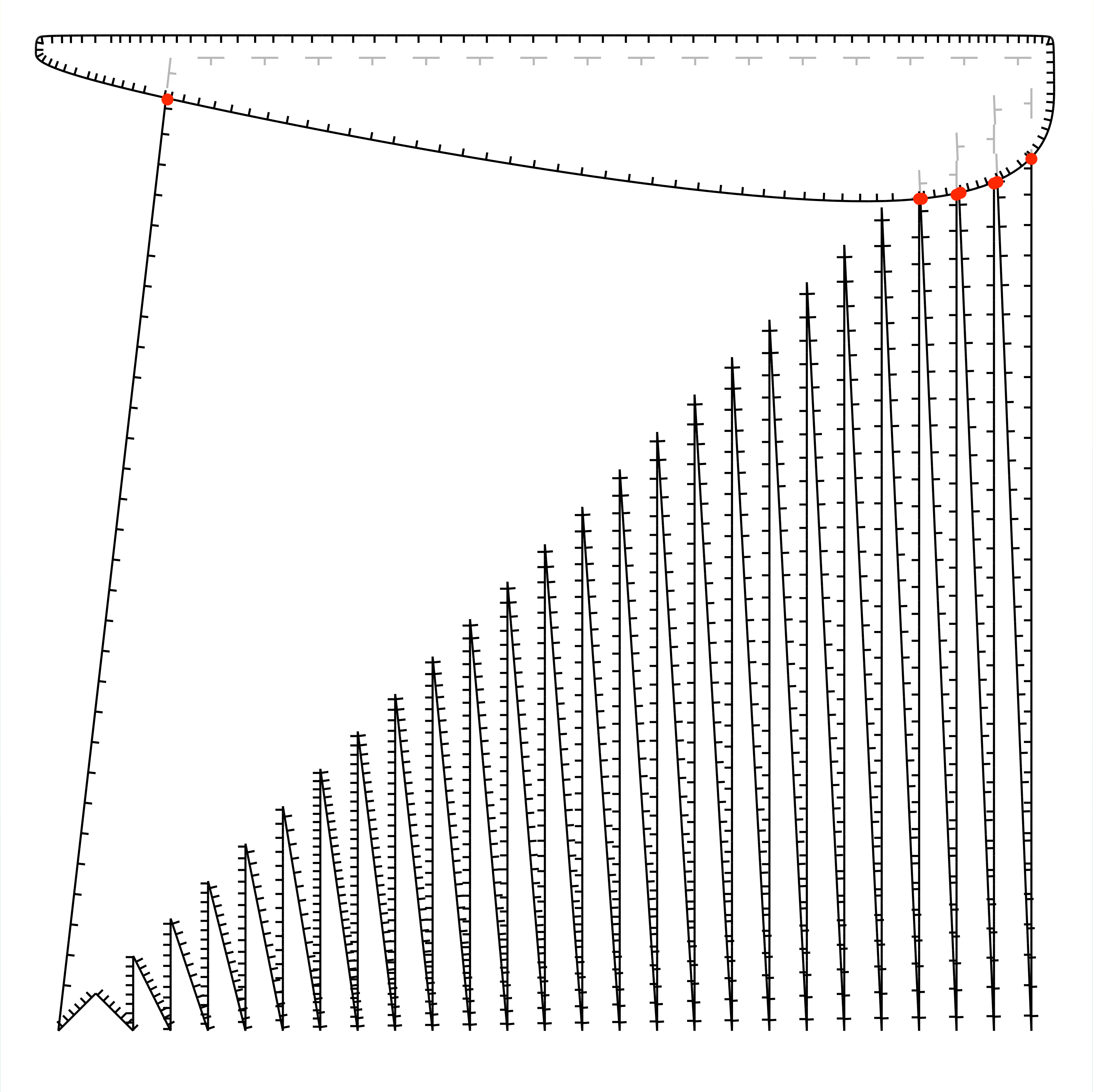
50

CSEC Flip Performance



Flipped CSEC size: linear in the total number of crossings

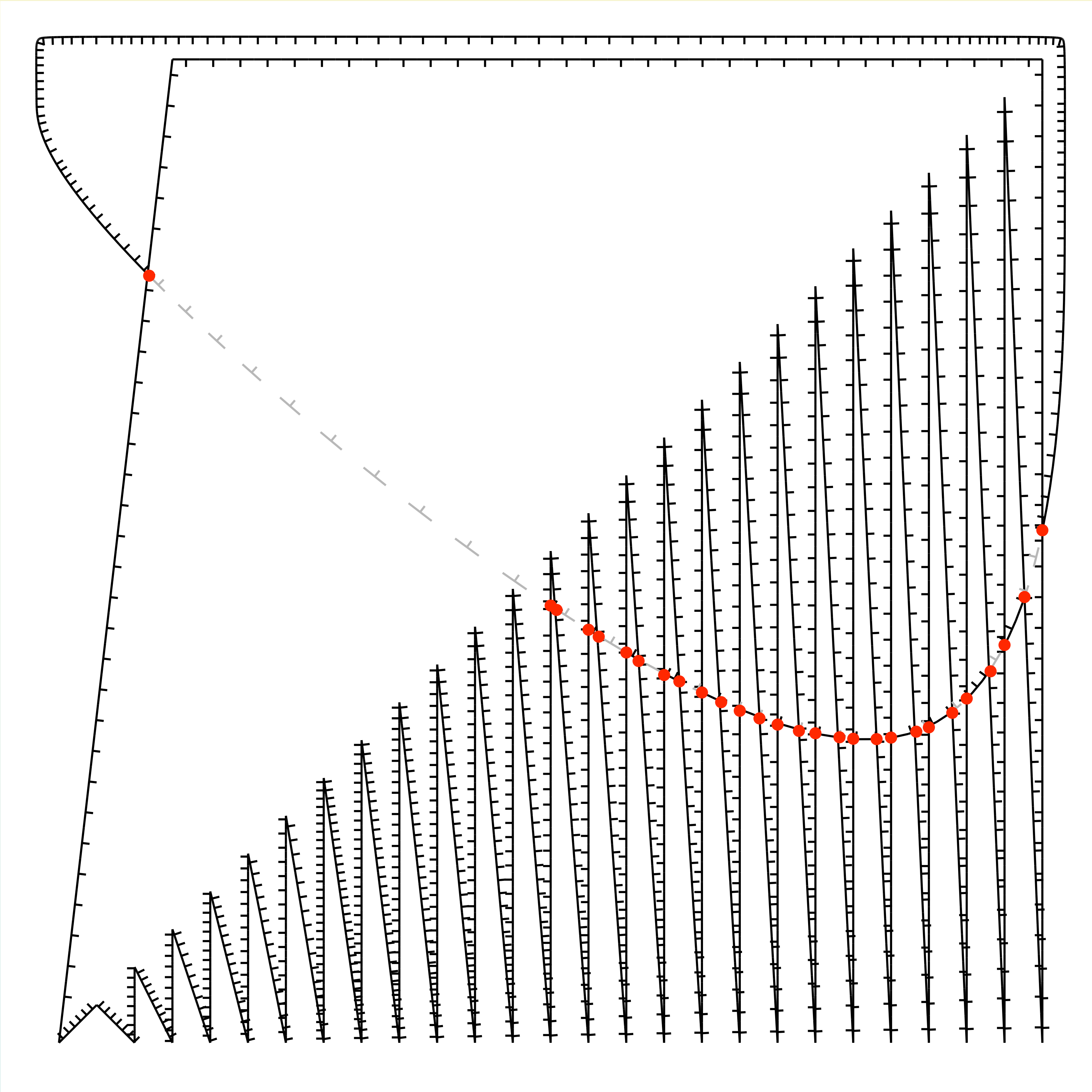
CSEC Flip Performance



Flipped CSEC size: linear in the total number of crossings

50

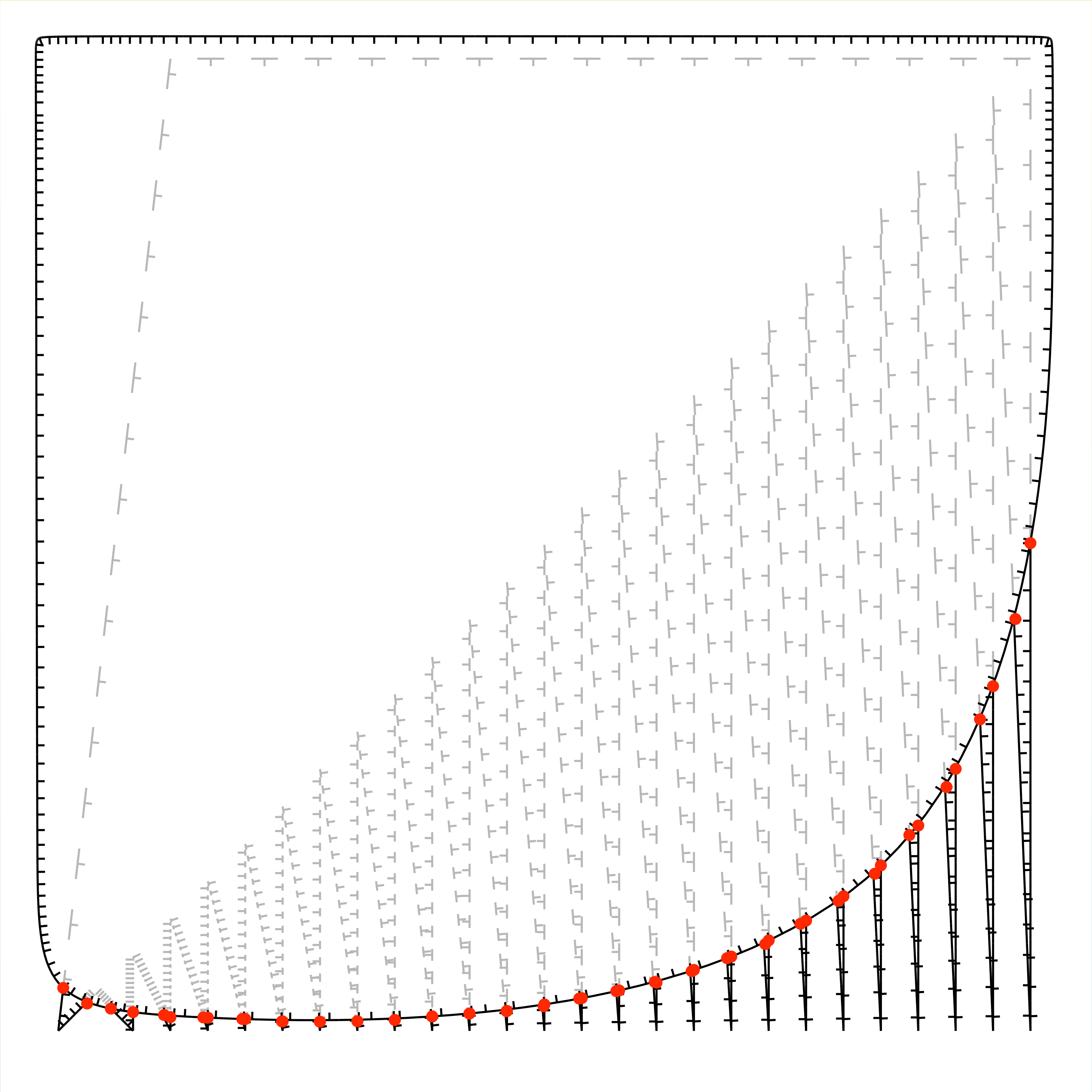
CSEC Flip Performance



Flipped CSEC size: linear in the total number of crossings

50

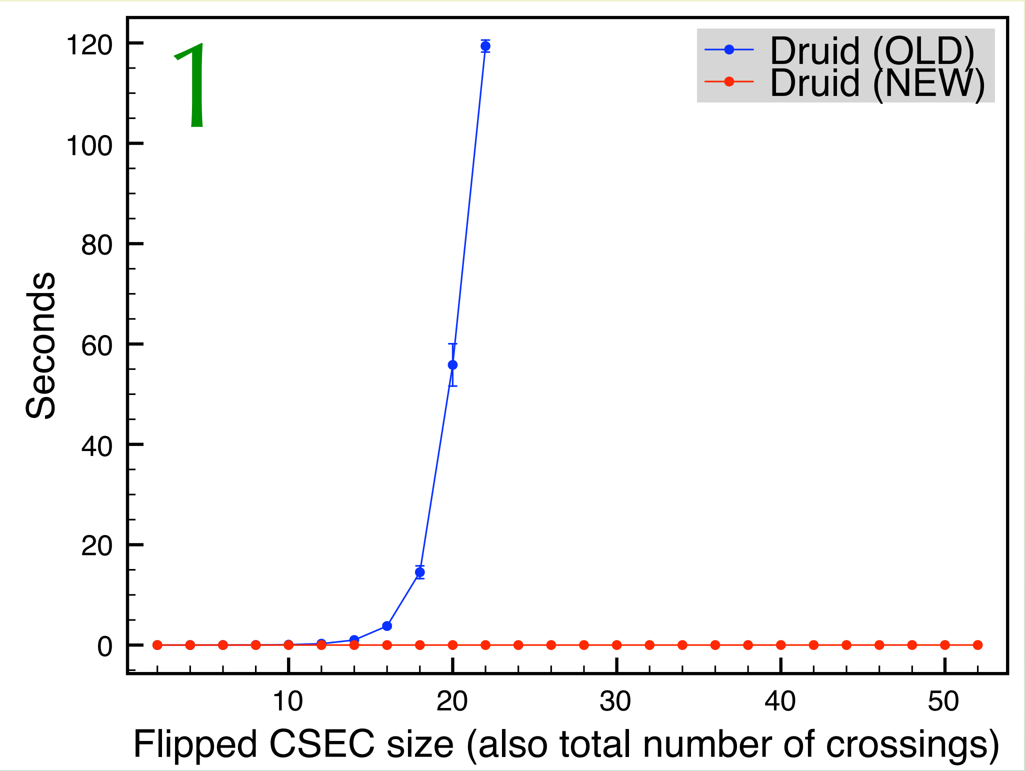
CSEC Flip Performance

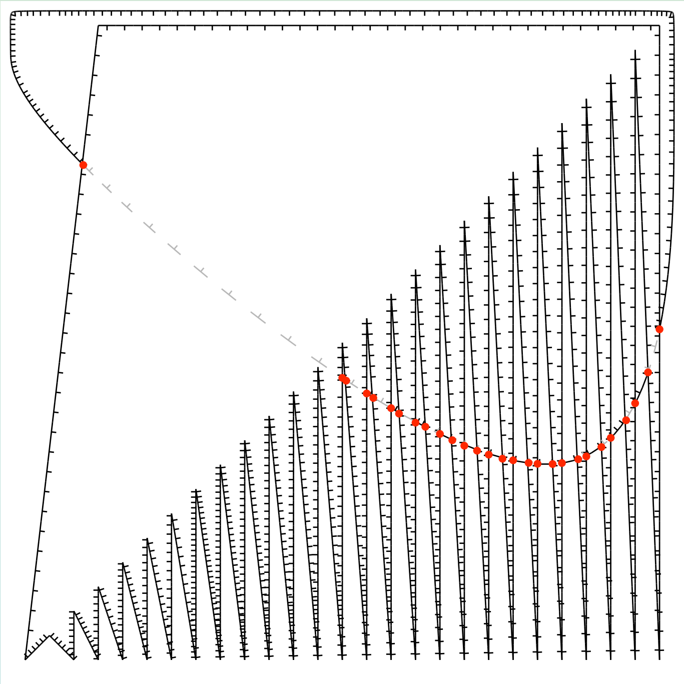


Flipped CSEC size: linear in the total number of crossings

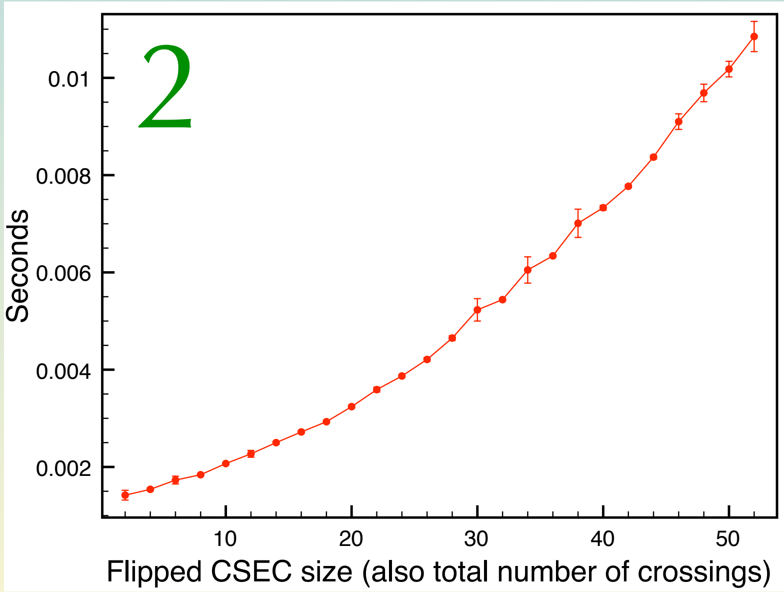
CSEC Flip Performance

Running time vs. CSEC size

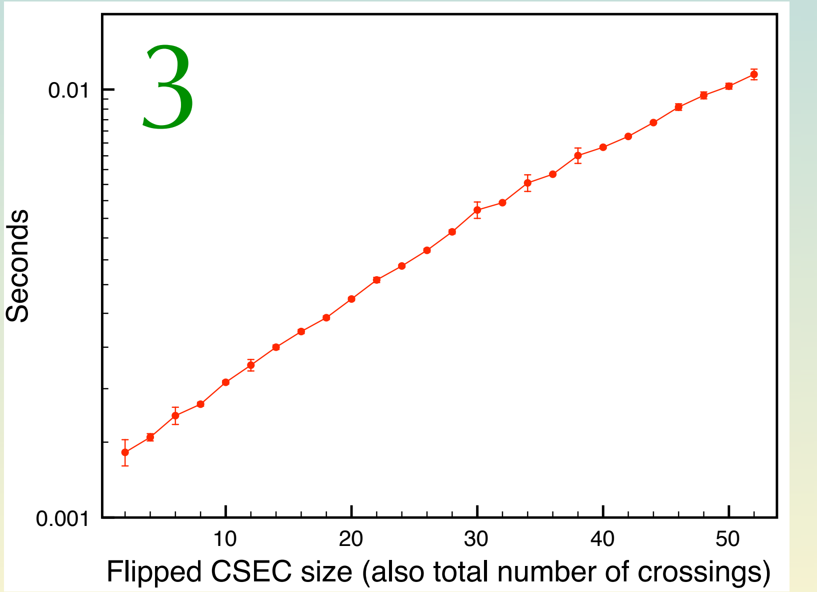




CSEC Flip Performance (*Druid* (NEW))

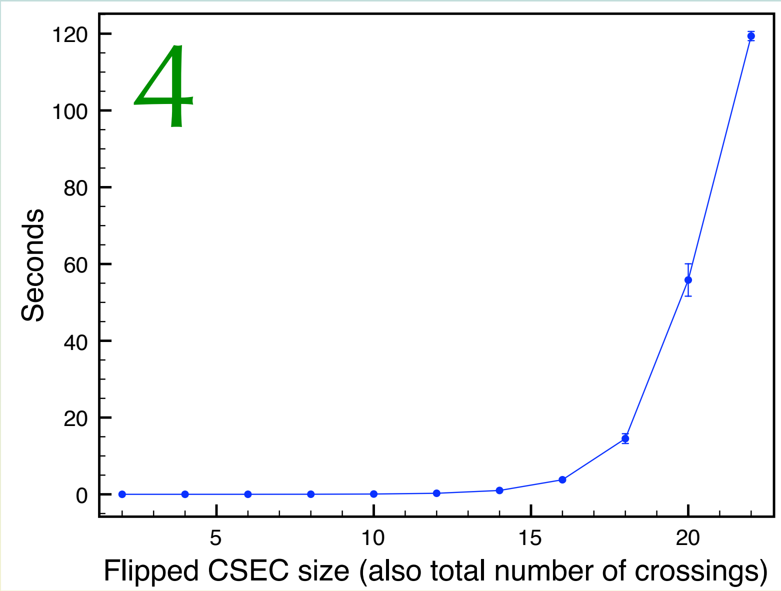


CSEC Flip Performance (*Druid* (NEW))
(log Y axis)

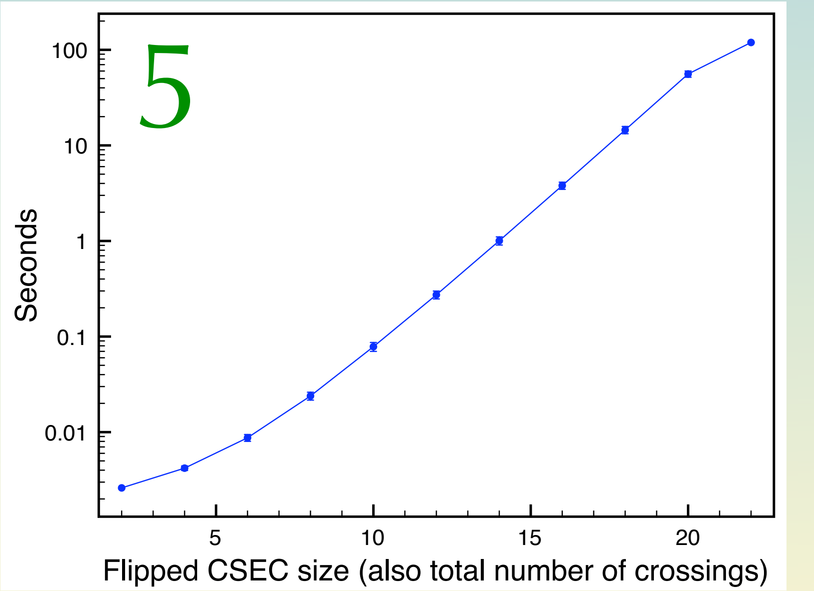


Performance is polynomial w.r.t. CSEC size

Search Performance (*Druid* (OLD))



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



Performance is exponential w.r.t. CSEC size

Conclusions

- Developed *Druid*, a system for constructing interwoven 2½D scenes.
- Use of branch-and-bound search to label; 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.

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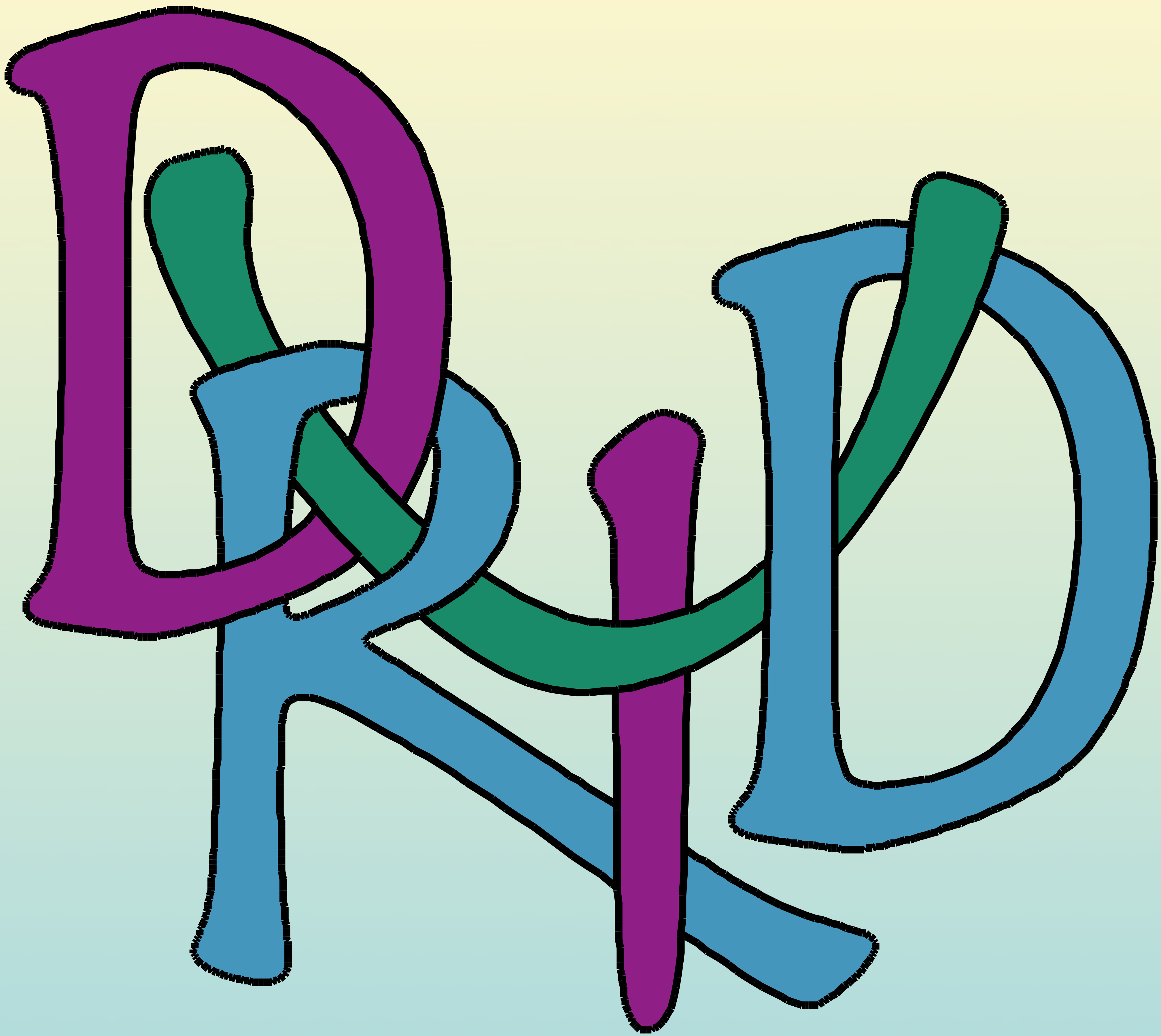

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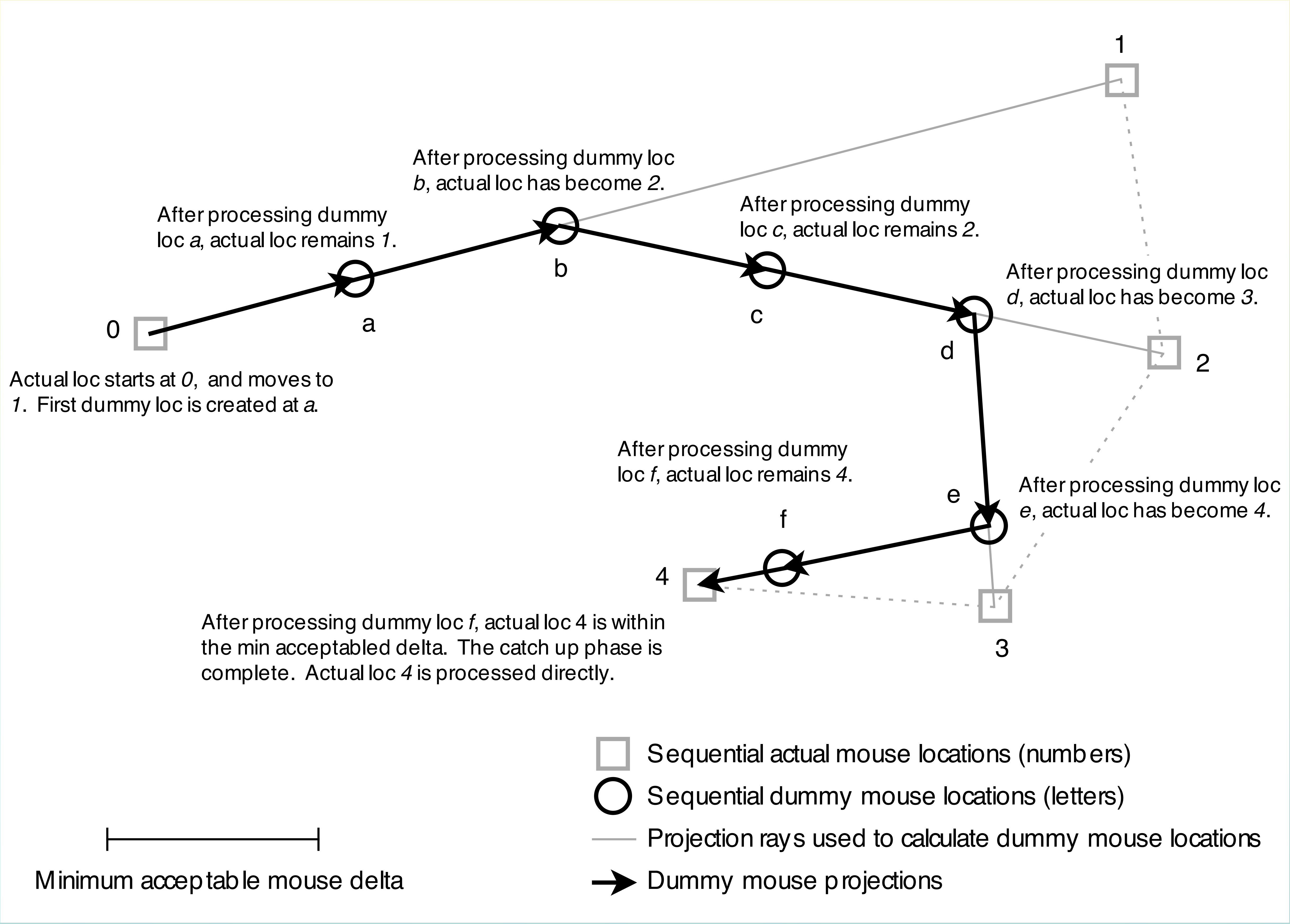
Min. Acceptable Mouse Delta



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