Switched Systems
and
Motion Coordination:
Combinatorial Challenges

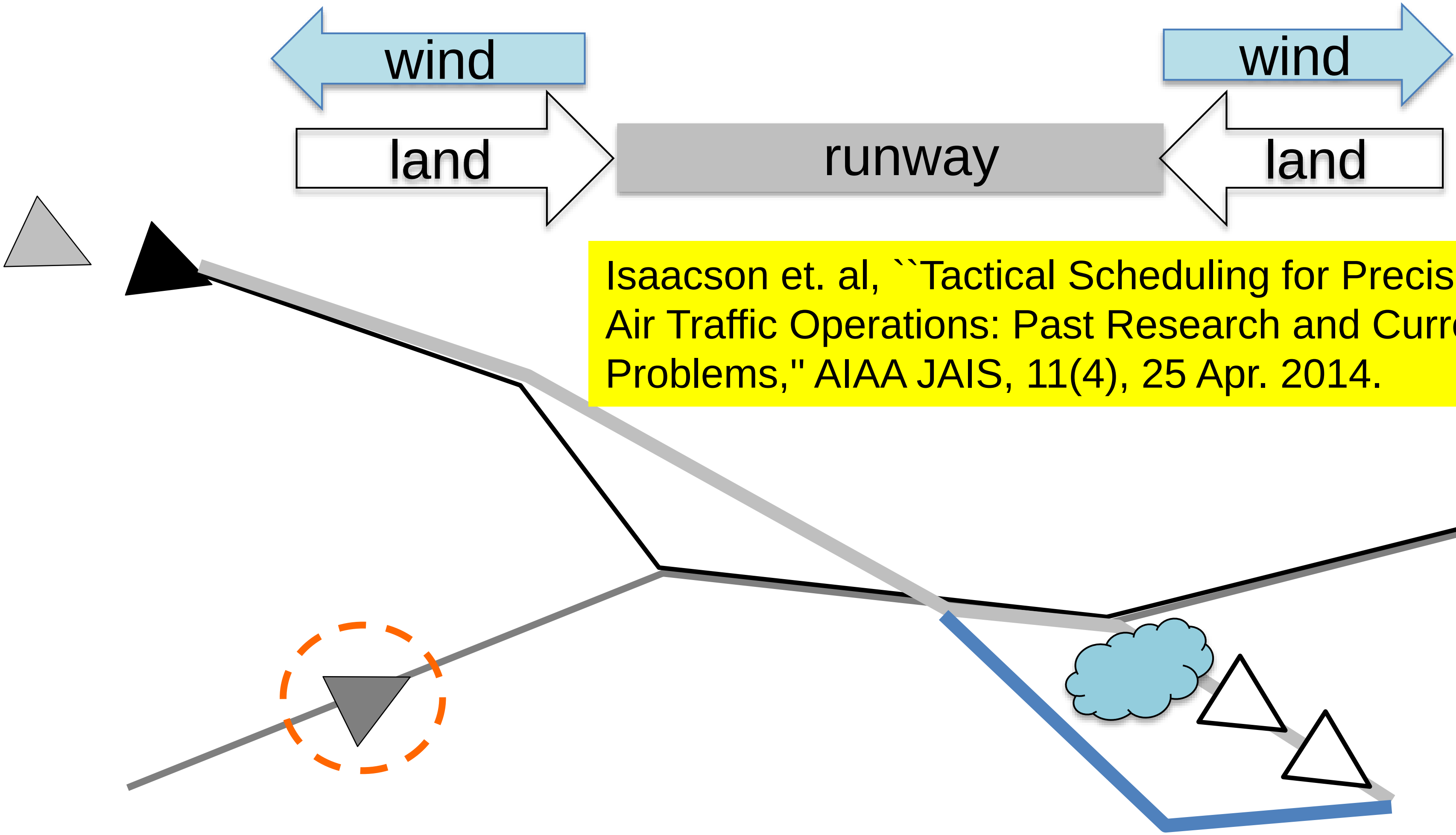
Alexander V. Sadovsky

NASA Ames Research Center

Outline

- Air Traffic Management (ATM): a rich source of switched systems problems
  - ATM as motion coordination in a route network
  - Scales of processes in ATM
  - Motion coordination as a switching system
- Related literature and the gaps
- Other challenges
- What is desirable at higher Technology Readiness

Air Traffic Management (ATM) as Motion Coordination in a Route Network



Isaacson et. al, ``Tactical Scheduling for Precision Air Traffic Operations: Past Research and Current Problems," AIAA JAIS, 11(4), 25 Apr. 2014.

Switched Systems can help with automation in ATM!

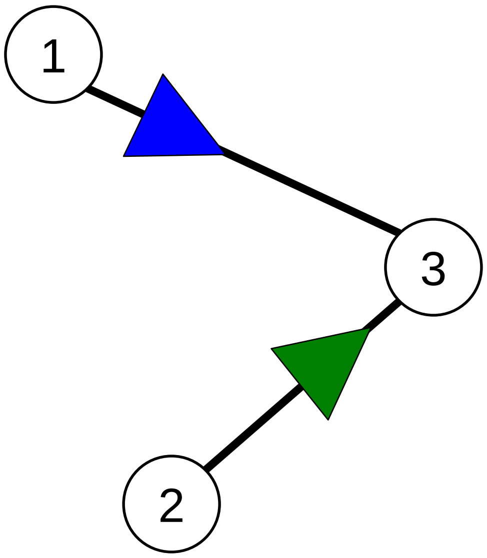
Air Traffic Operations in U. S. Airspace: Scales

- Flights simultaneously ariborne:
  6,000 – 7,000 at peak hours
- Traffic Flow Management (TFM) time scales:
  - Strategic routing: ~2-6 hrs
  - Tactical routing: <~2 hrs
  - Separation assurance: ~10 mins
- Terminal space size 60-80 nmi around the airport
- Human controller workload (~15-20 aircraft in sector)

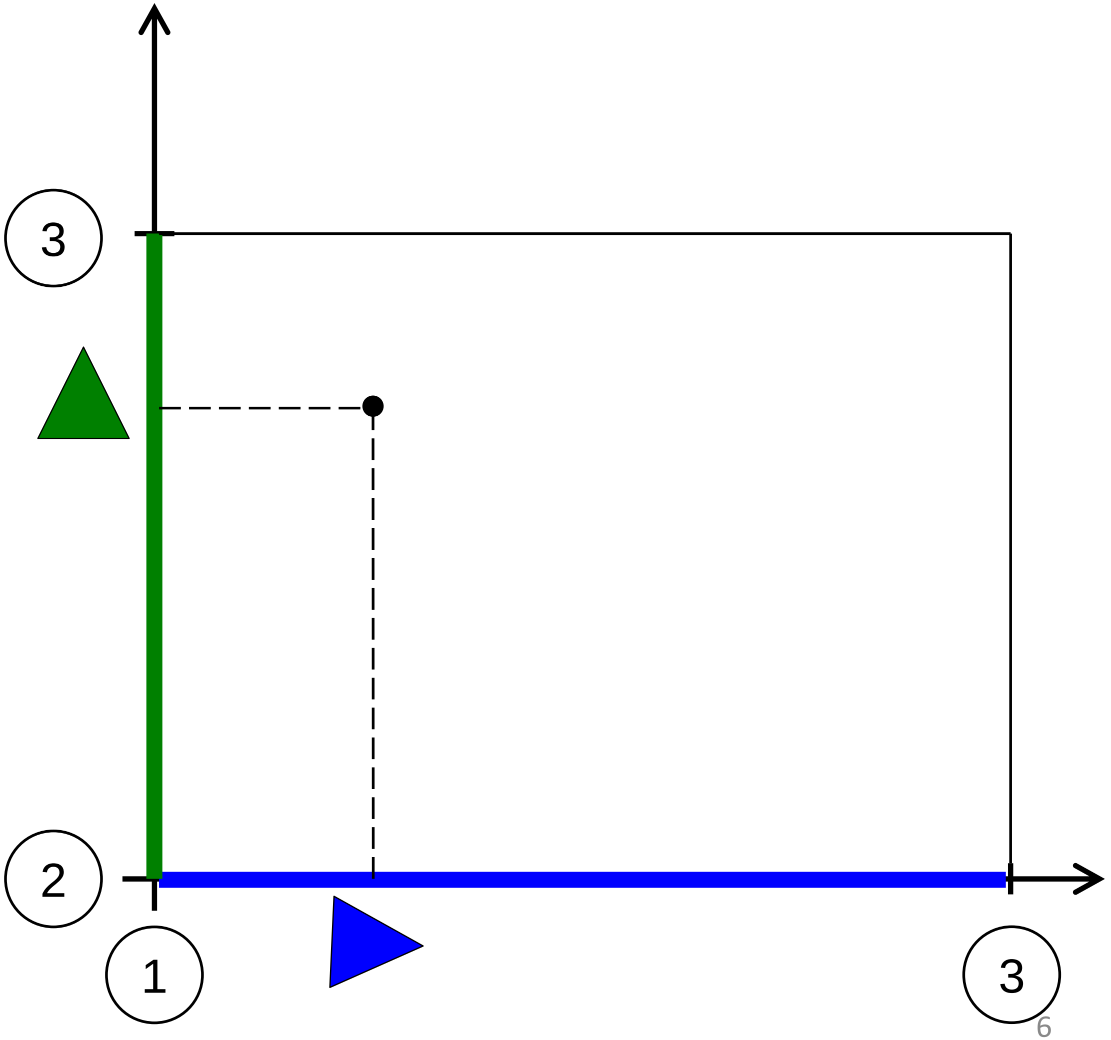
Constraints: An Operational View

- Distance separation requirements
- Merging routes
- Division of responsibility for safety (human vs. automation) – today, mostly human
- Airspace restrictions
- Performance bounds (acceleration, pitch, etc.)

Physical airspace



State space



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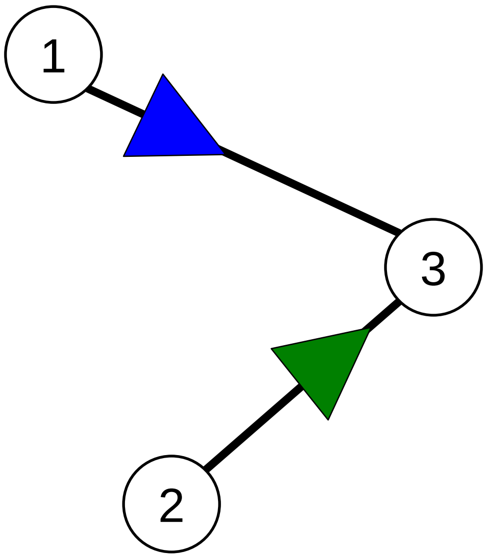

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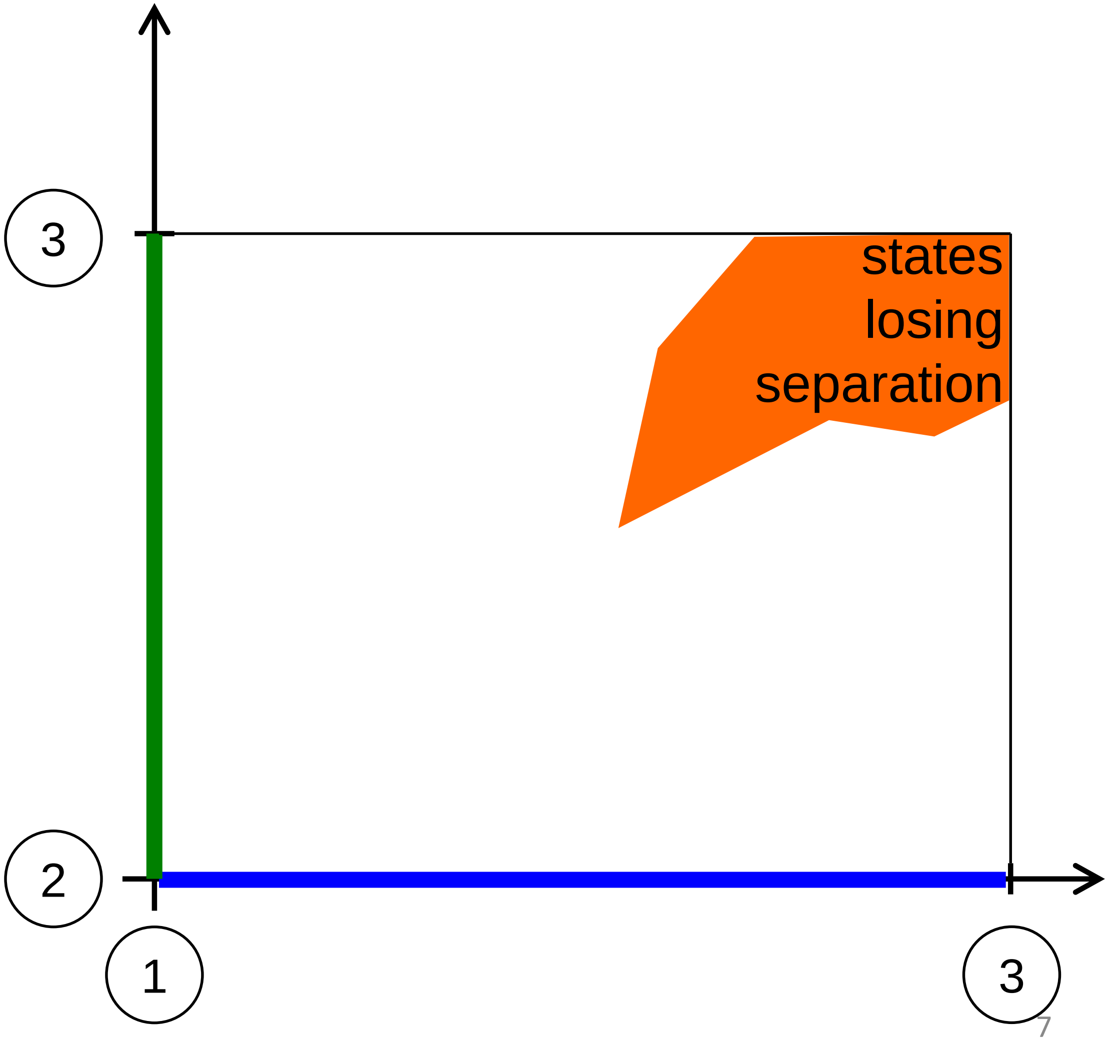

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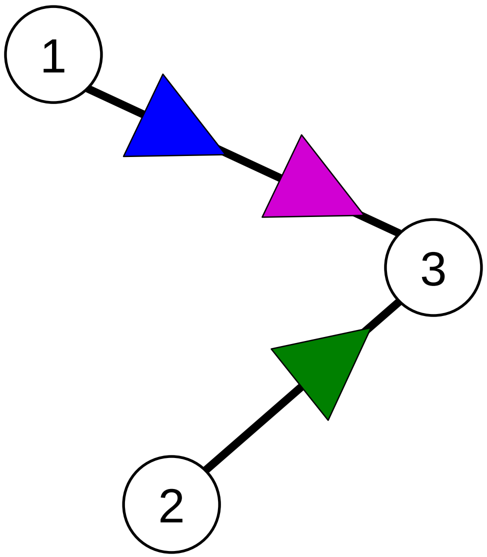
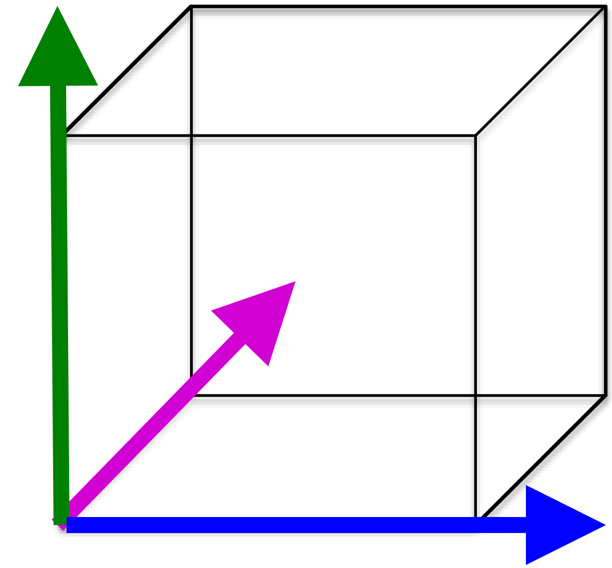
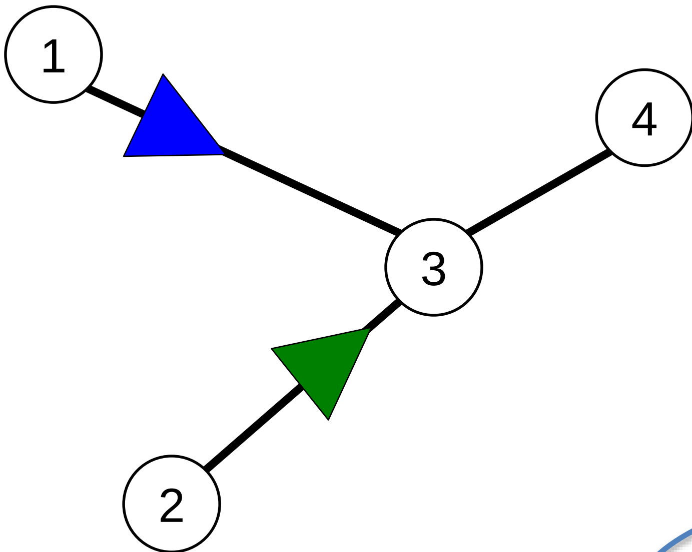


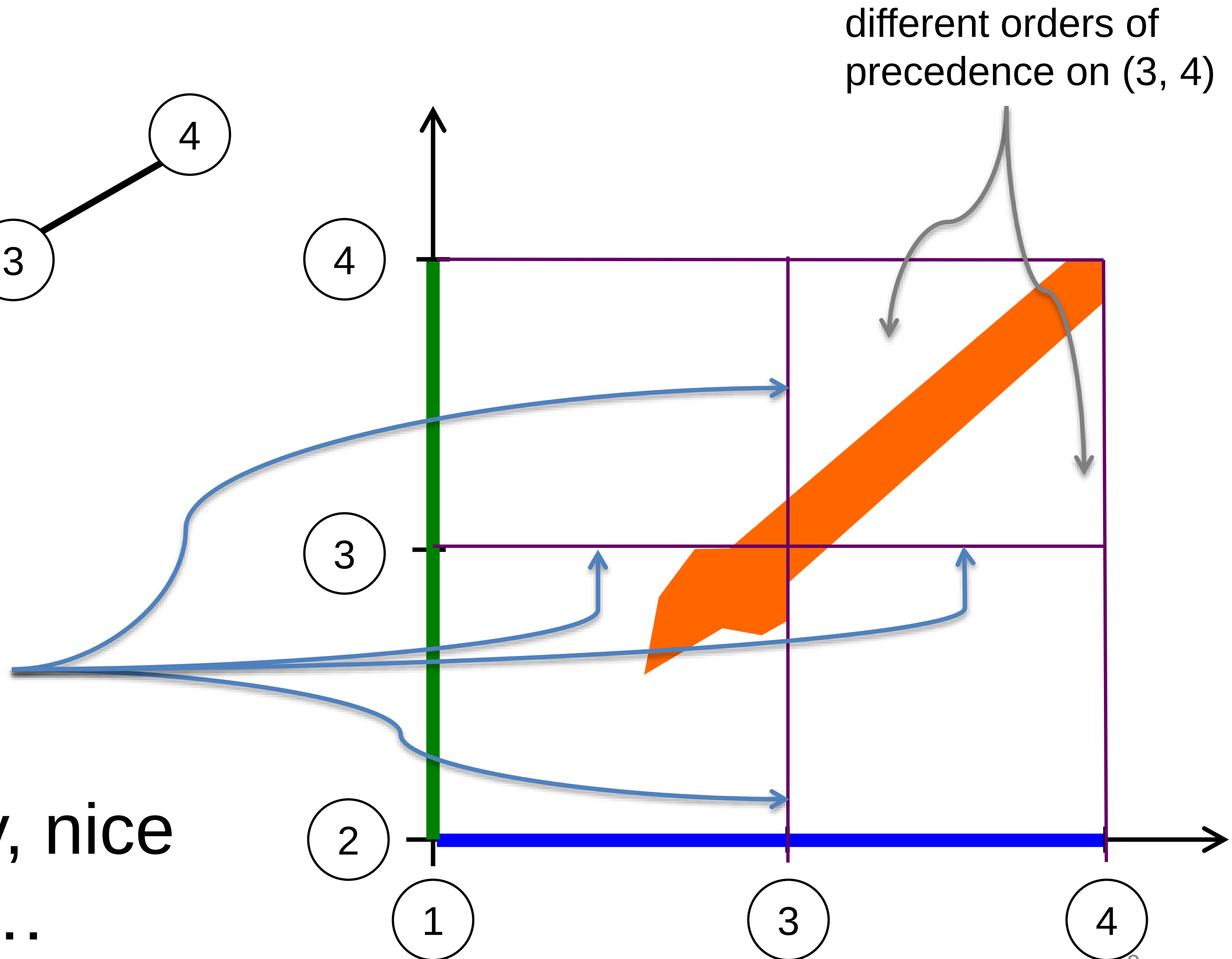
State space



Physical airspace

State space

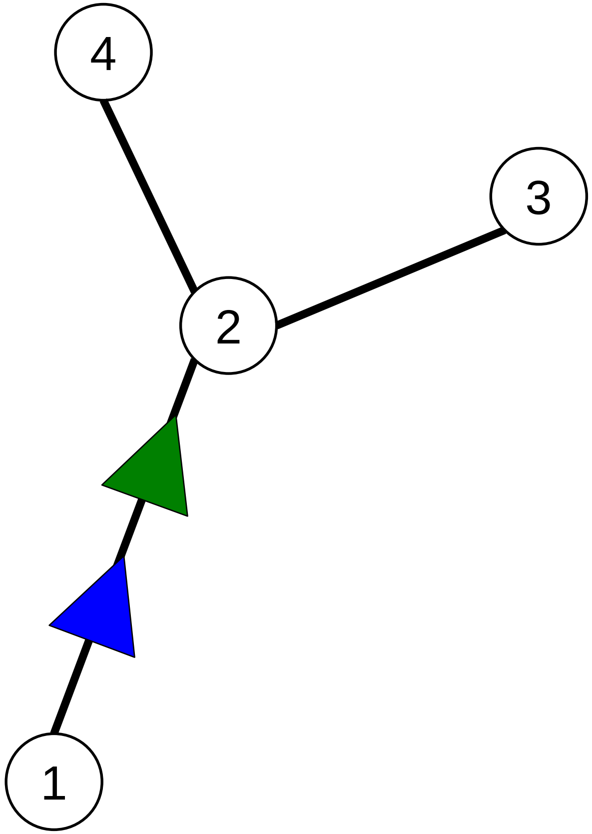




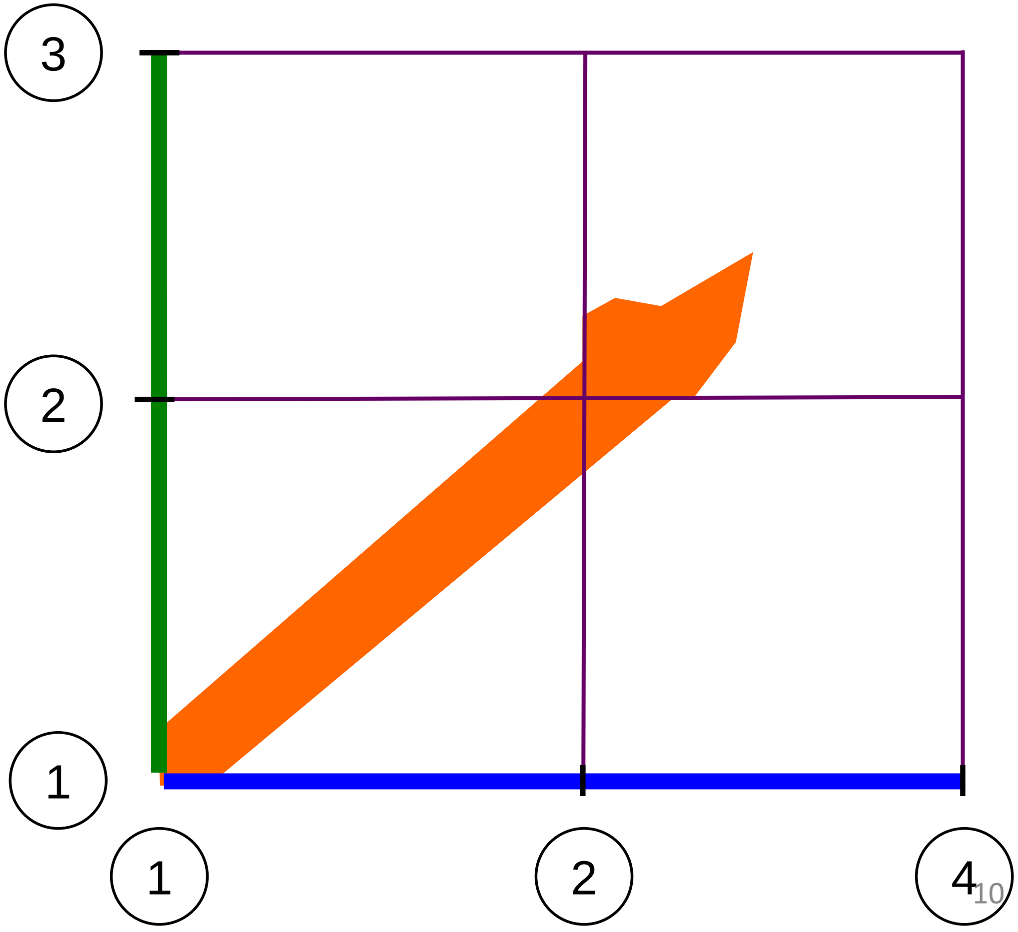
switching surfaces

apparently, nice geometry…

Physical airspace



State space
(only part of)



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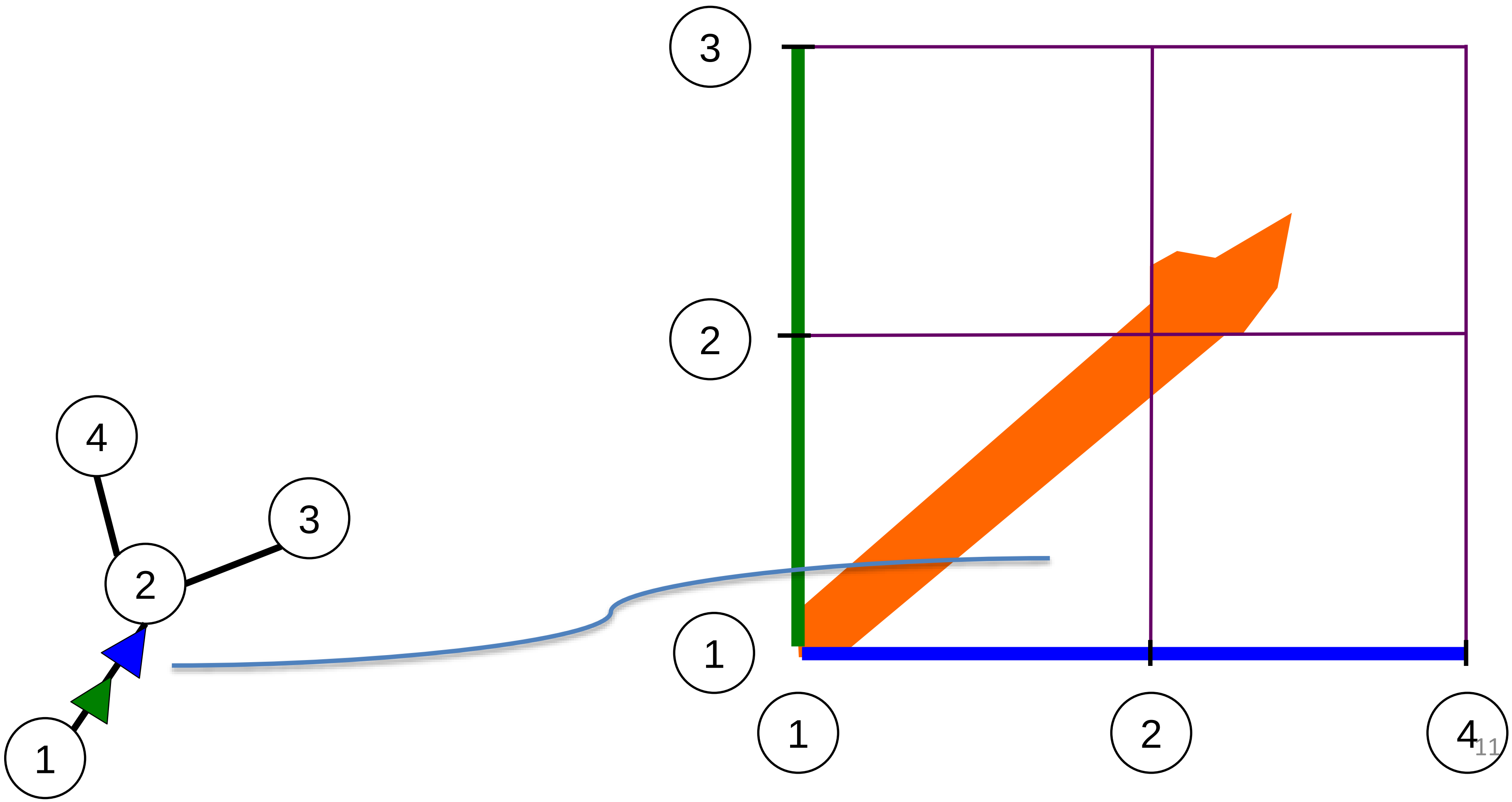

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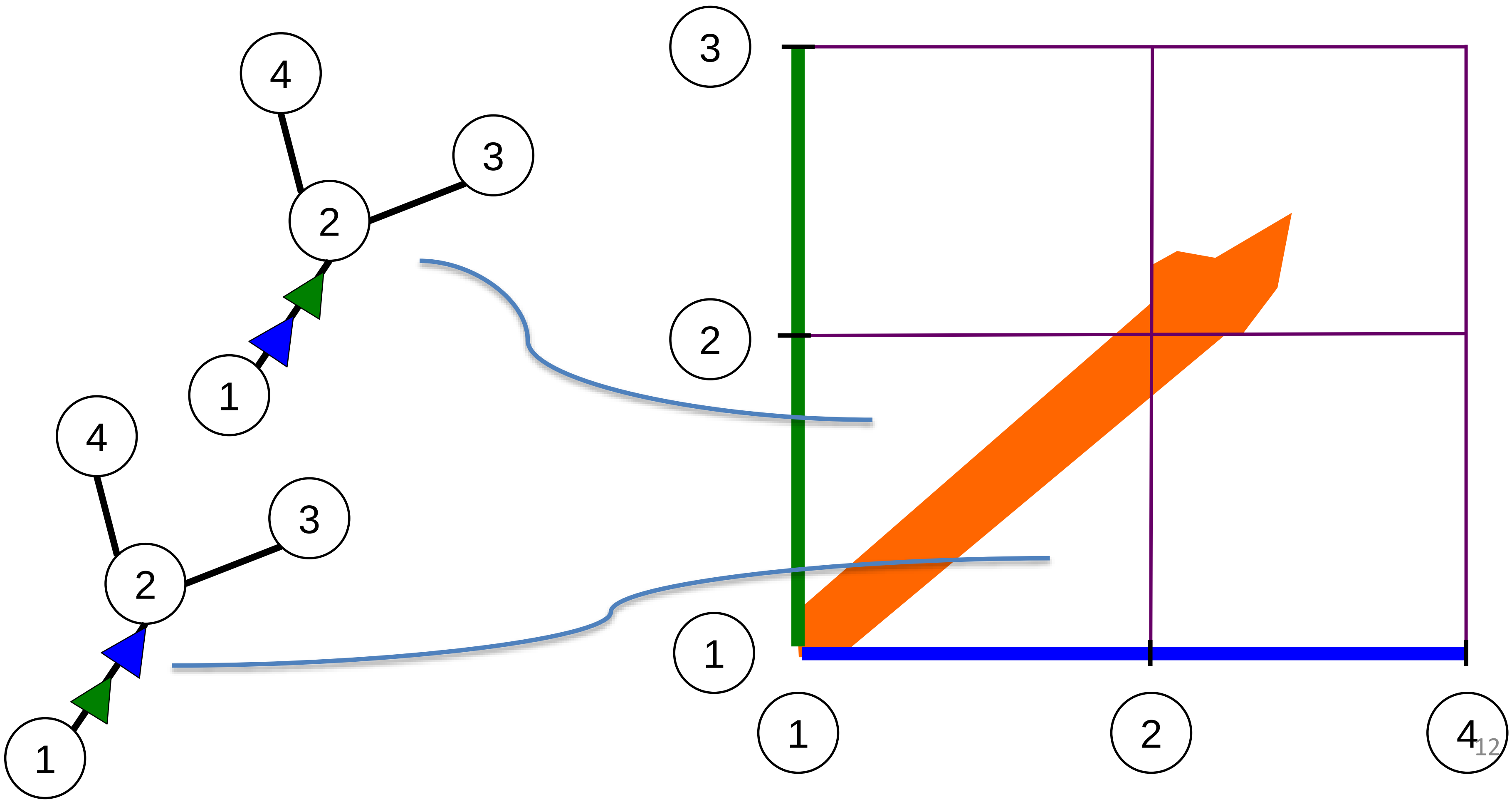

Physical airspace

State space
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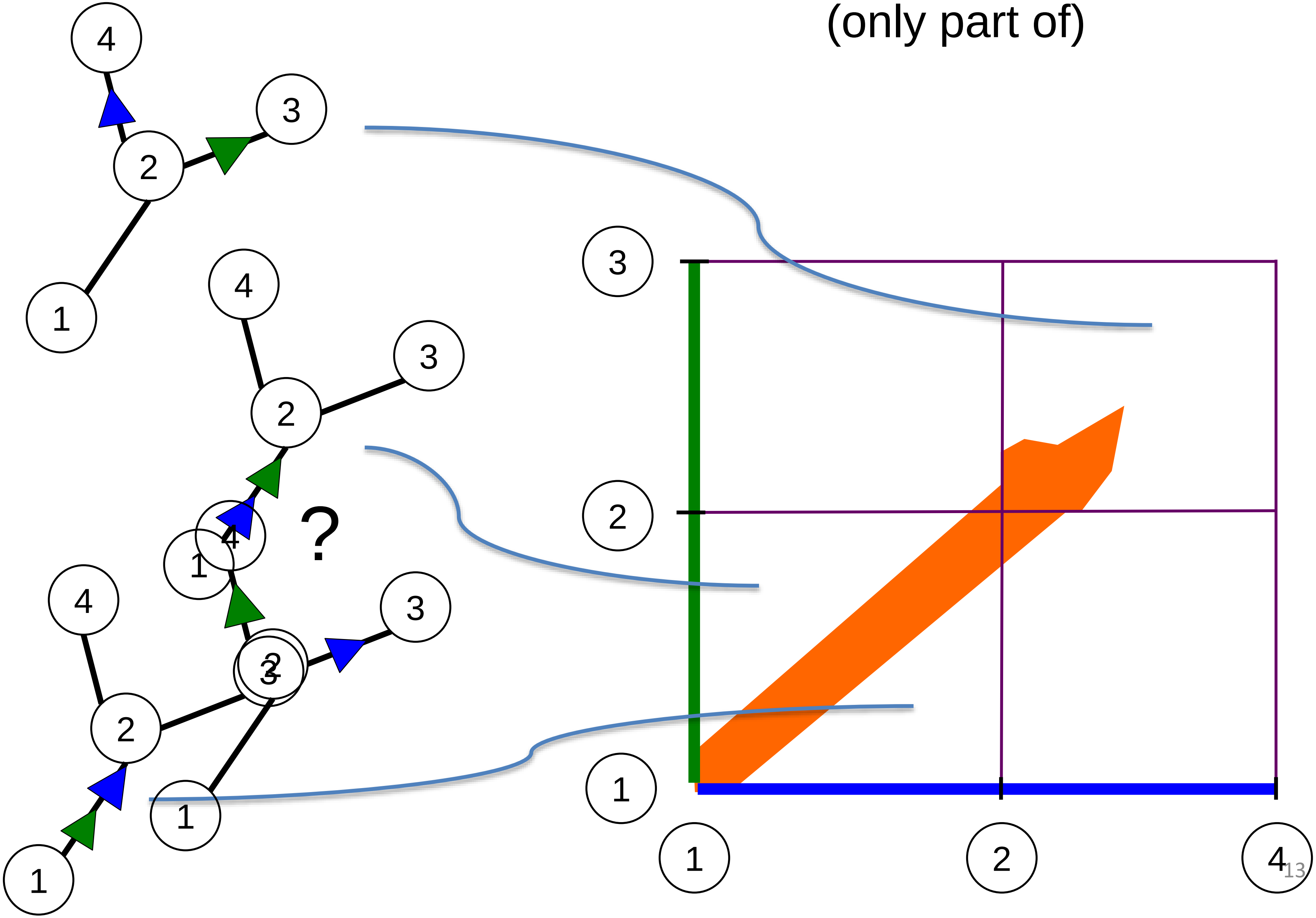

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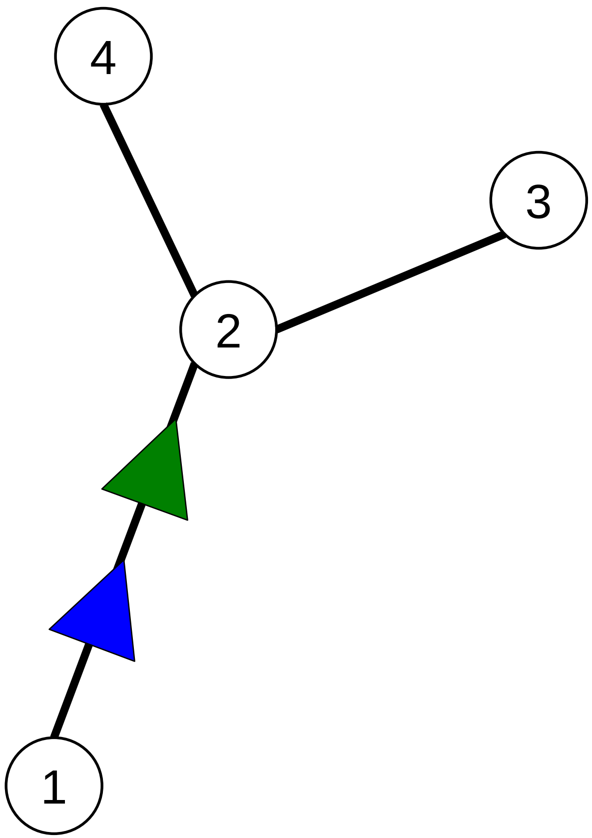
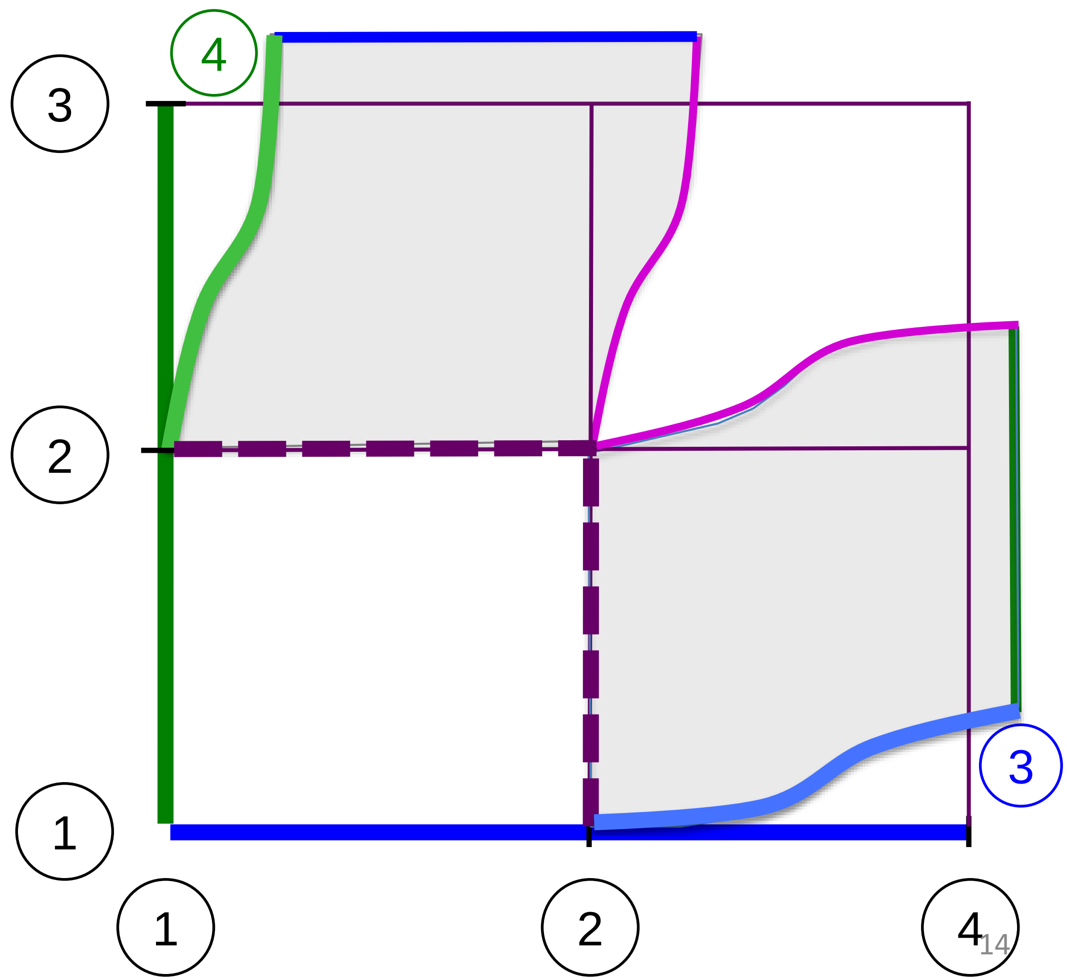
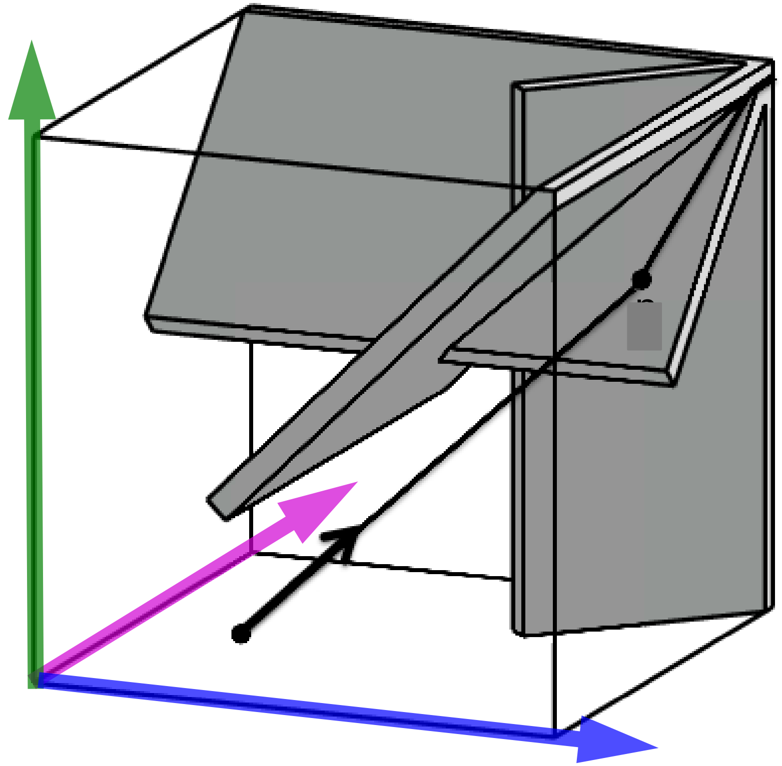


State space
(still only part)



A 3-aircraft example



Sadovsky et. al.,
“Efficient Computation of Separation-Compliant Speed Advisories for Air Traffic Arriving in Terminal Airspace”,
ASME . Dyn. Sys., Meas., Control 136(4)

Related literature and the gaps

source(s)	content	assumptions absent in ATM
Dmitruk et. al.: Systems and Control Letters 57(11)	get hybrid Maximum Principle from classical	sequence of discrete modes is given
Bengea et. al.: Automatica 41(1)	optimal control of switching systems by embedding	system has no memory
R. Ghrist et. al., papers on “coordination”	multi-agent coordination in a route network	routes known

Related literature and the gaps

source(s)	content	assumptions absent in ATM
Passenberg et. al.: 49th IEEE Confer-ence on Decision and Control Issue 0191-2216	maximum principle for hybrid systems with partitioned state space	partitioned state space (regional dynamics)
Rezaei et. al.: AIAA Journal of Guidance, Control, and Dynamics doi: 10.2514/1.G001779	algorithm for feasible hybrid control of arrival flights, with proof of correctness and bounds on computational cost	• all flights fully routed • only arrivals • only one landing runway • piecewise speed profiles • no wind

Other Challenges: Proprietary Data

- **Question**:
  How to model aircraft control realistically for non-local, strategic navigation in terminal airspace?

- **Challenge(s)**:
  Standard Operating Procedures, Flight Management Systems, and Flight Management Computers (brains of FMS) vary by airline and by manufacturer, and are *proprietary*.

FAA guidance on developing SOPs: FAA document AC-120-71a.
For FMS, some specifications are in ARINC 424.

Other Challenges:

Regulation-imposed Constraints on Air Traffic Ops

- **Question**:
  How to model airspace and separation constraints realistically?

- **Challenge(s)**:
  – Constraints vary discontinuously by:
  aircraft type, airspace type, and specific airspace.
  – Boundary of safety envelope generally not smooth.

- Isaacson et. al., "Tactical Scheduling for Precision Air Traffic Operations," AIAA JAIS, 11(4), 25 Apr. 2014.
- C. Arendt, "Optimal control of fully routed air traffic in the presence of uncertainty and kinodynamic constraints," Ph.D. Thesis, 2014.

Other Challenges:
State Space Geometry

- **Question**:
  How to (or should one) parameterize a route network for multi-agent motion?

- **Challenge(s)**:
  When one agent reaches the end of its route segment, another is in the middle of its segment. State space *not* a surface.

- A. Sadovsky, "Application of the Shortest-Path Problem to Routing Terminal Airspace Air Traffic," AIAA JAIS, 11(3), 2014

Other Challenges:

Uncertainty (weather, facility malfunctions, control execution)

- **Question**:
  How to model uncertainty?

- **Challenge(s)**:
  Limitations of probability theory.

- Vervoort, L. "A detailed interpretation of probability, and its link with quantum mechanics." arXiv preprint arXiv:1011.6331 (2010).

What is desirable at higher Technology Readiness Levels (TRL)

- Transparent analysis for:
  - Correctness
  - Reliability
  - Regulation compliance
- Real-time computation
- Solutions physically executable
- Feasible cost to industry

Summary

- Air Traffic Management research offers many problems in switched systems
- Multiple spatial and temporal scales; e.g., distinguish:
  - En Route airspace
    (prescribed routes, high altitude, room to hold, strategic planning)
  - Terminal airspace
    (sometimes procedures instead of routes, may not have room, many merging routes, more tactical in nature)
- Publications and other information at:

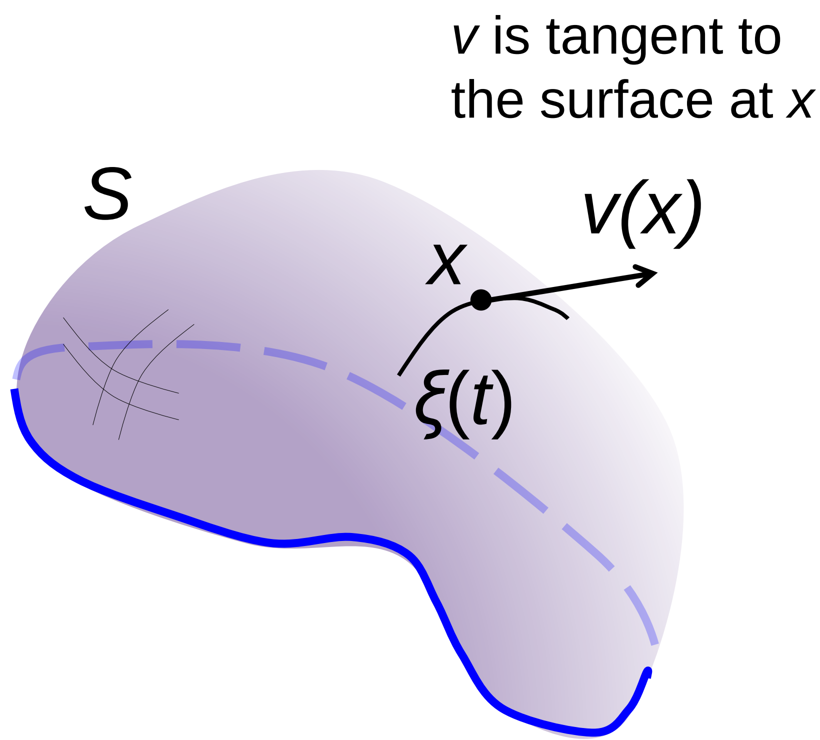
  www.aviationsystemsdivision.arc.nasa.gov/

- Thanks to D. Isaacson, NASA ARC

- Thank you for your attention

Backup Slides

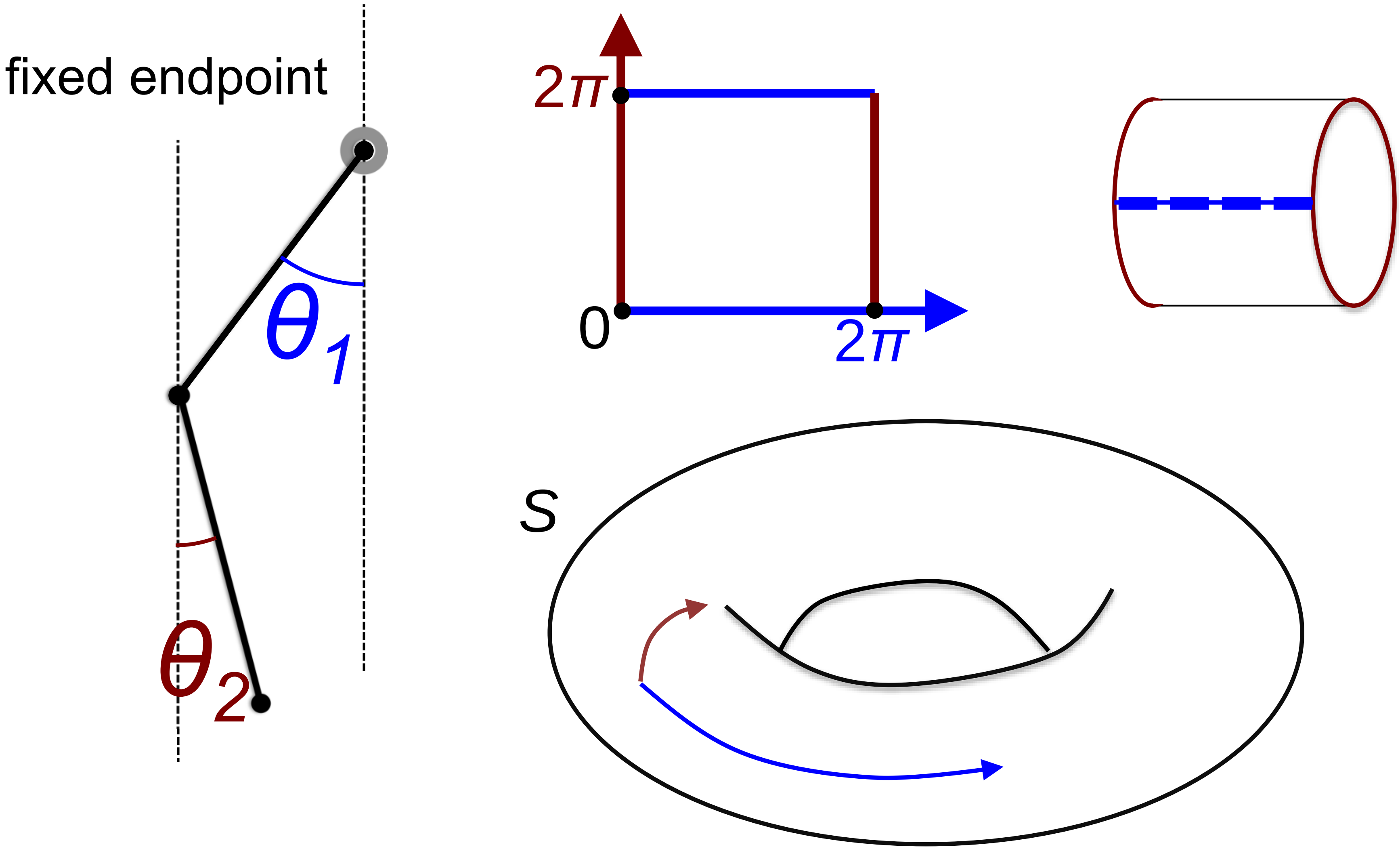
The geometry of a dynamical system



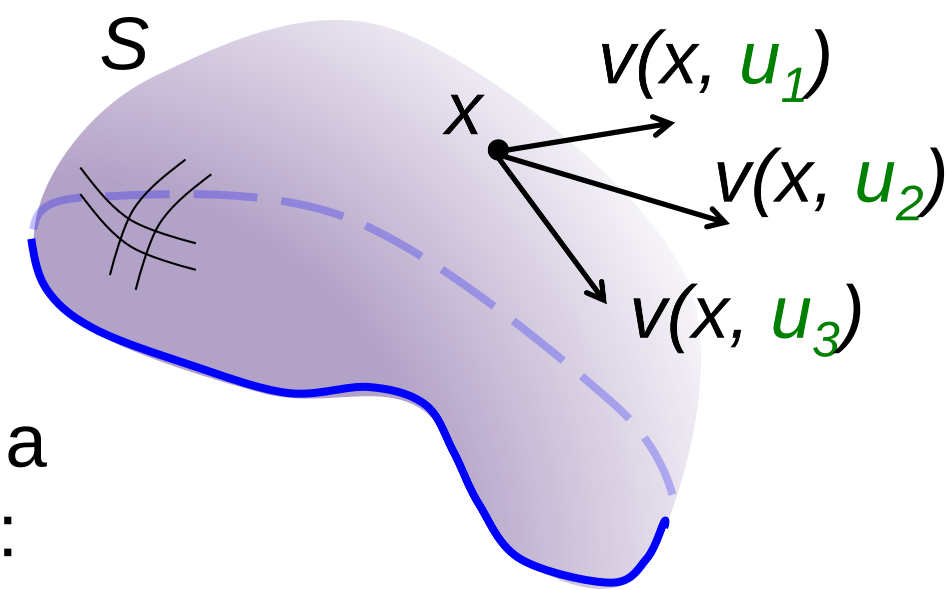
Solving for such
a *ξ*(t) on *S* that:

$$\left.\frac{d}{dt}\right|_{t=t} x(t) = v(x) \text{ when } x(t) = x$$

Example: a double pendulum with no inertia



The geometry of control



Solving for such a $u(t)$ (or $u(x)$) that:

the resulting $\xi(t)$ goes where and how we want.