Bayesian OODA loops with MIDAS:

Augmented decision making in a complex future electromagnetic environment

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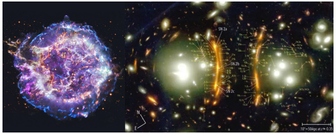
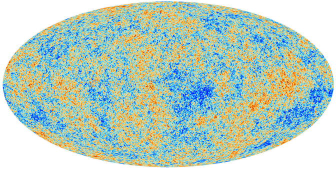
Background: Bringing Bayesian Astrostatistics back to Earth





Astrophysicists interested in:

- Quantify uncertainty
- Fusion of diverse measurements
- Biggest data

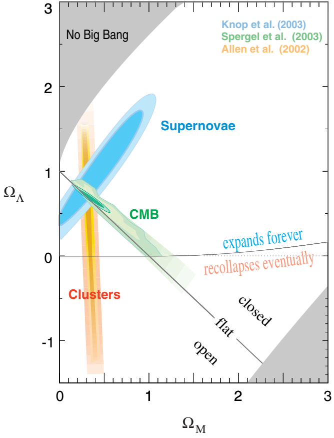
Typically use Bayesian methods:

- Incorporation of prior info
- Quantifies updating knowledge
- Bayes theorem: unifying framework

$$P(H|D) = \frac{P(D|H)P(H)}{P(D)}$$

H : Hypothesis
D : Data

Complementary to machine learning



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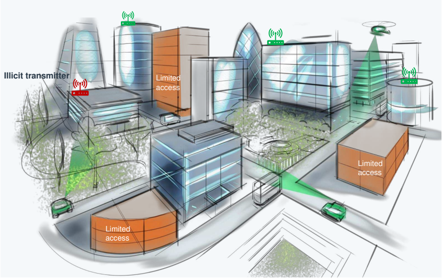
Background: Challenges in the Electromagnetic Environment (CEME)

Since 2020 participated in 6 Maths of CEME workshops, with 5 DSTL-funded projects

1. Optimising a search route to discover networks in a landscape of constraints *(CEME1.2, [Jan20])*
2. Optimisation of sensor location *(CEME2.3 [Sep20])*
3. Further optimisation of sensor location *(CEME4 [Sep21])*
4. MIDAS: Maximum information data acquisition strategies *(CEME6.4)* [Jan23])
5. Optimal dynamic manoeuvring & adaptation of communications networks driven by the MIDAS information-advantage mathematical framework *(DASA GAN [Oct23])*



DSTL: Olly Gage, Emily Russell, Ben Jackson, Ben Gear, Emma Bowley
PA: James Matthews, Richard Claridge, Emily Morrison, Rob Lambert
PC Ltd: Catherine Watkinson, Thomas Mcaloone, Parul Janagal, Adam Ormondroyd
UCAM/QML: Mike Hobson, Justin Ward, Oscar Bandtlow

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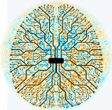
Background: PolyChord Ltd & Nested Sampling

Nested sampling

- Framework of numerical algorithms for performing Bayesian analysis
- Performs three tasks:
    1. Optimisation $\max_x f(x)$
    2. Exploration $x \sim f$
    3. Integration $\int f(x)dx$

  on a-priori unknown-functions
- Key algorithm called `polychord`
- Developed in my Cambridge cosmology lab



PolyChord Ltd

- Data Science SME spun out of Astro group
- Applies nested sampling & Bayesian machine learning to industry problems
- Working with PA/DSTL for three years
- Protein folding, Nuclear fusion, Battery optimisation, predictive maintenance.

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Toy example (conducted in CEME1 workshop):

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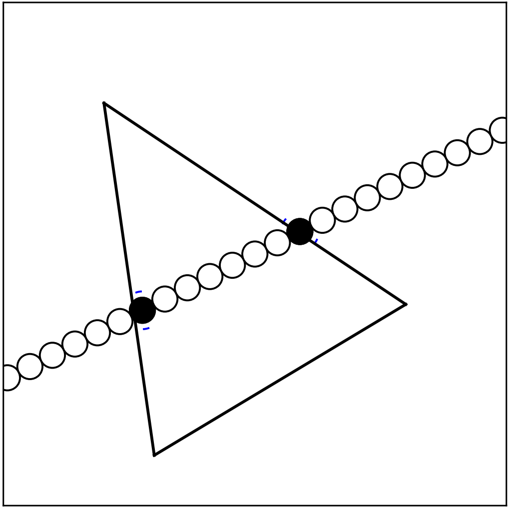

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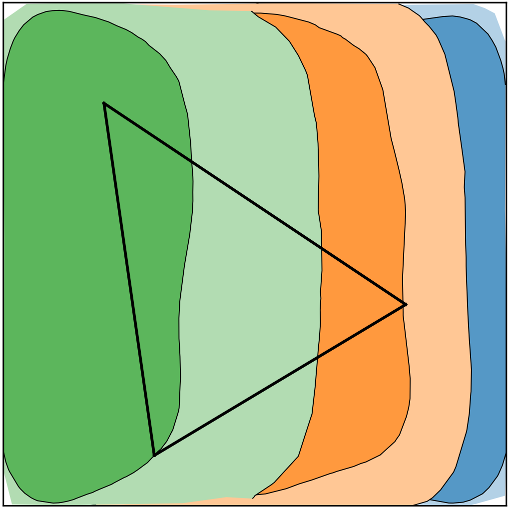

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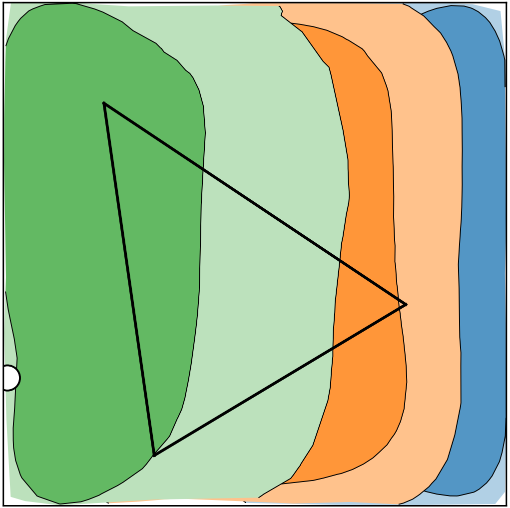

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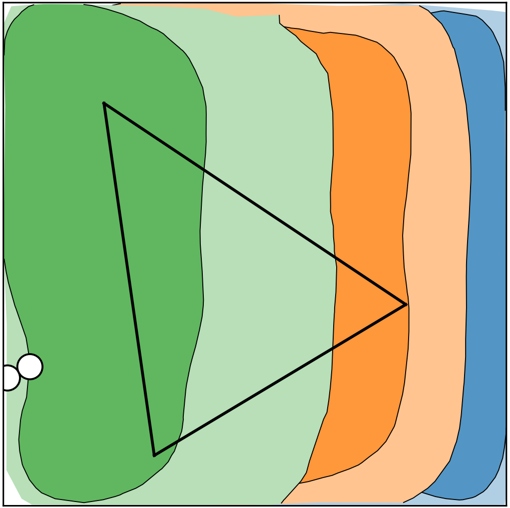

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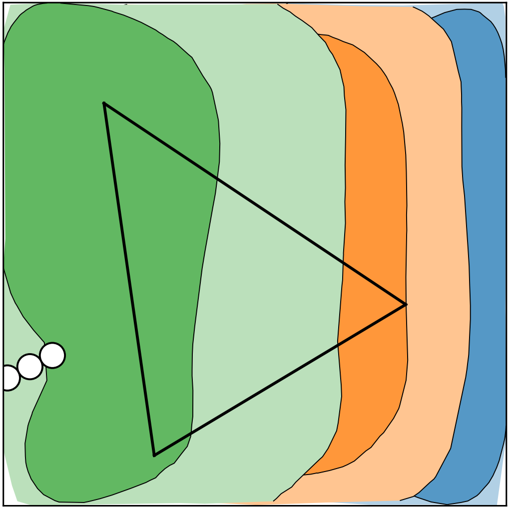

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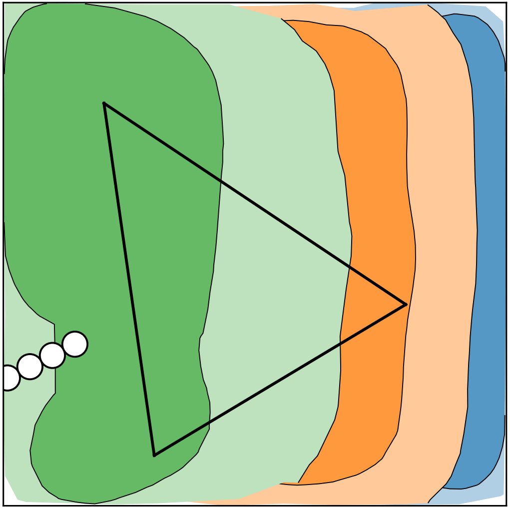

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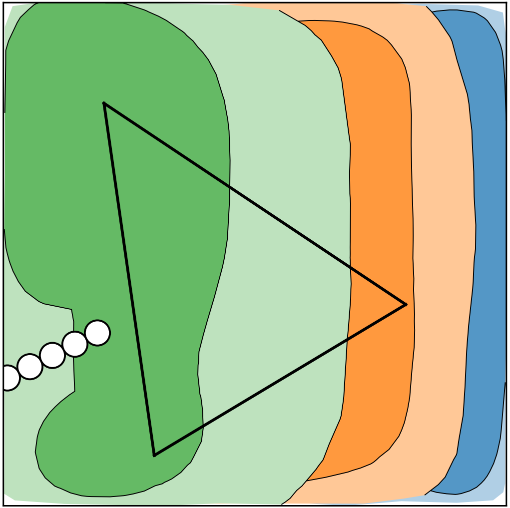

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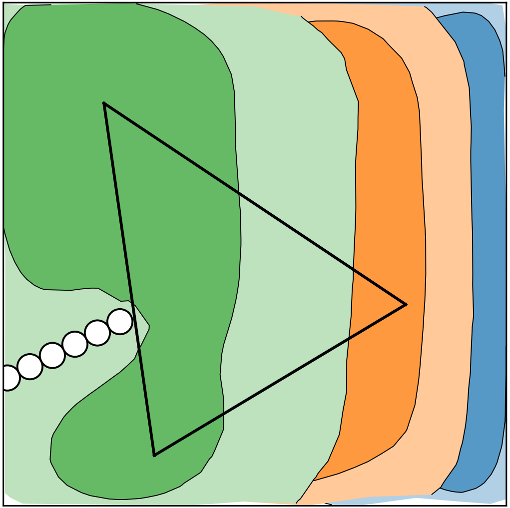

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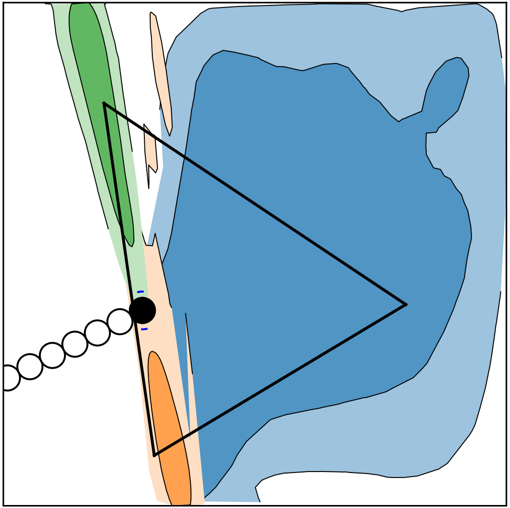

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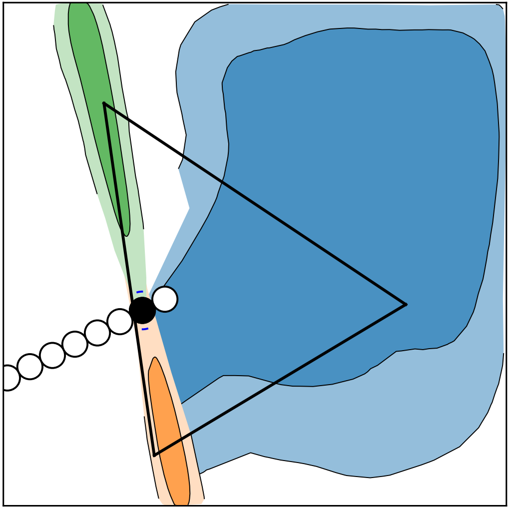

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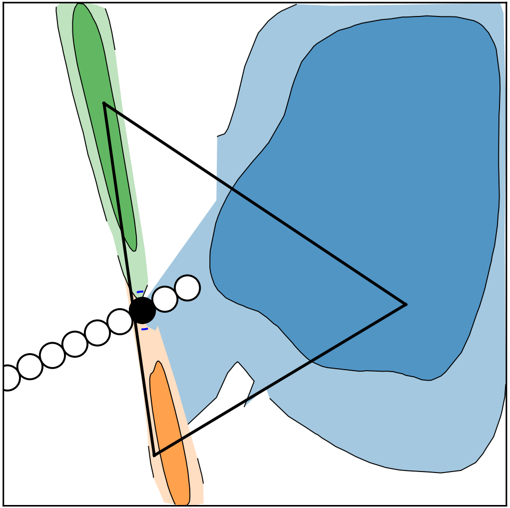

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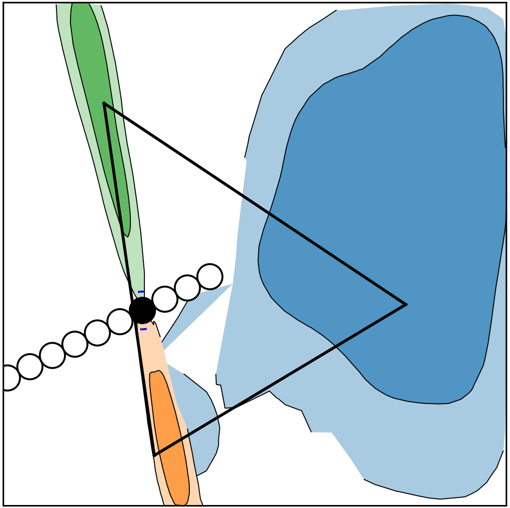

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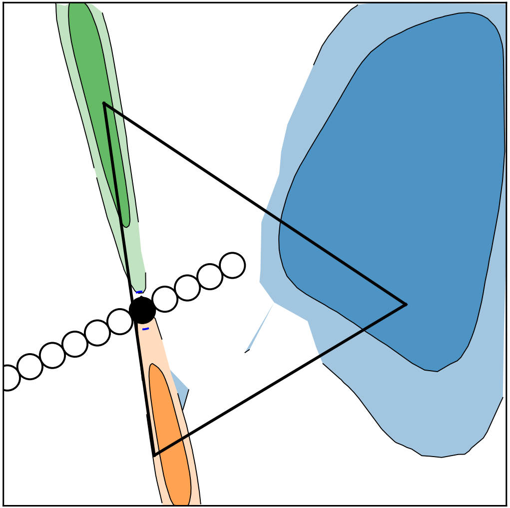

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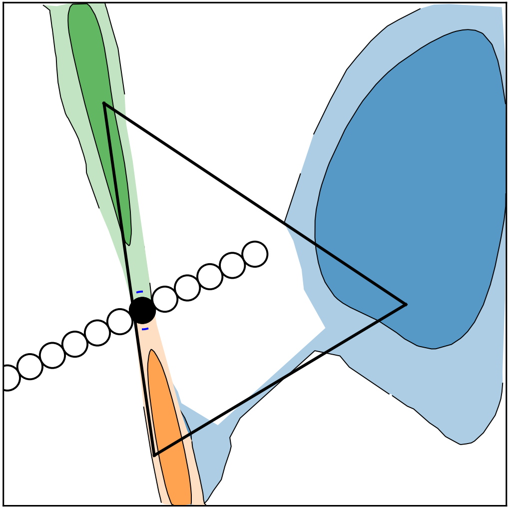

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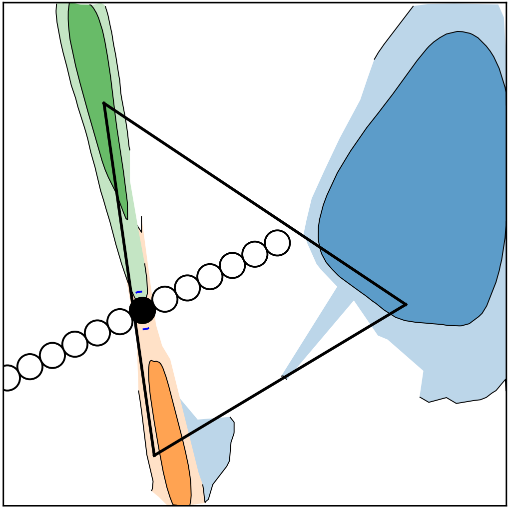

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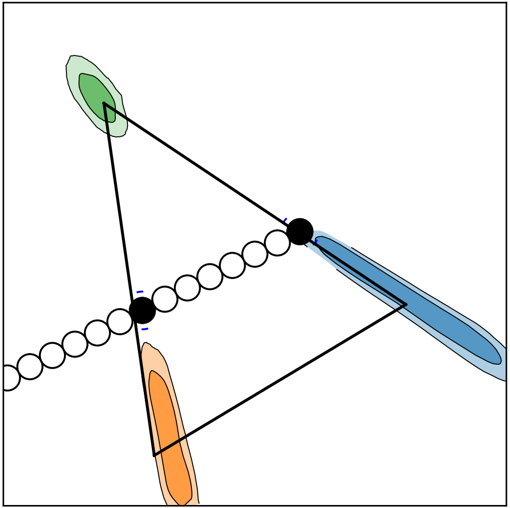

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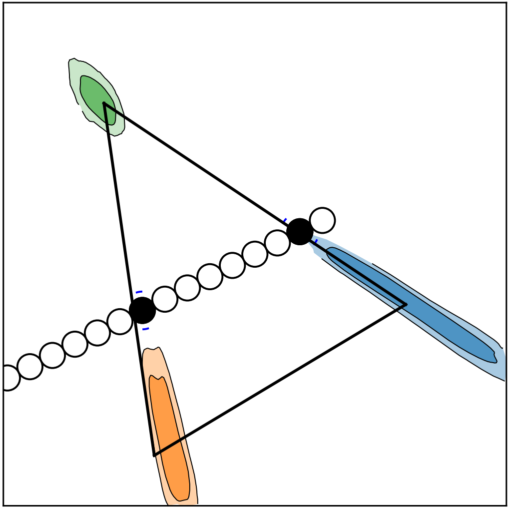

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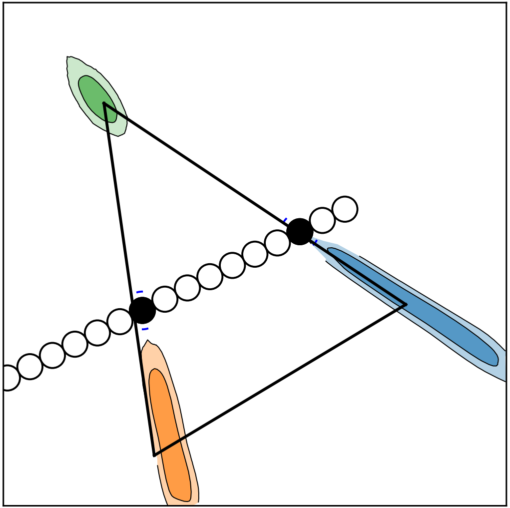

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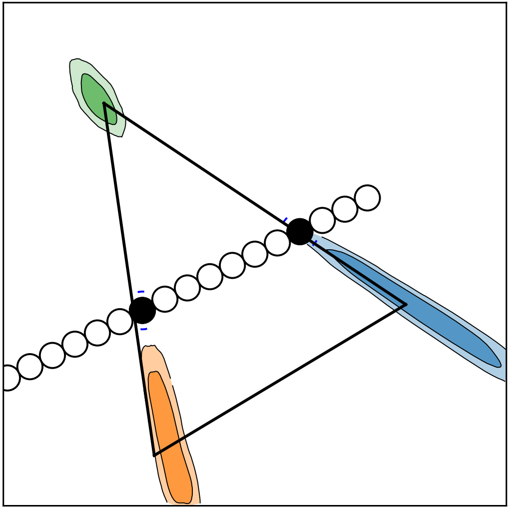

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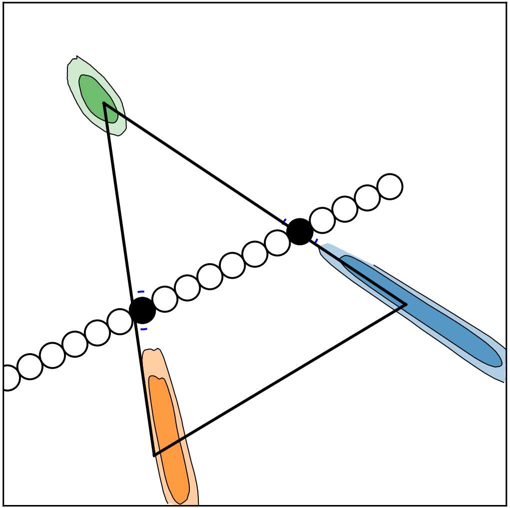

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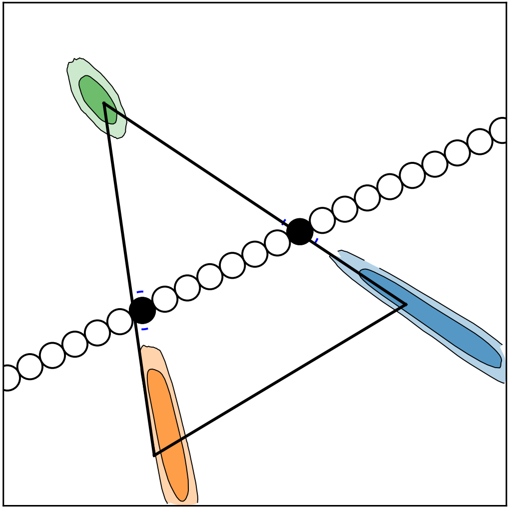

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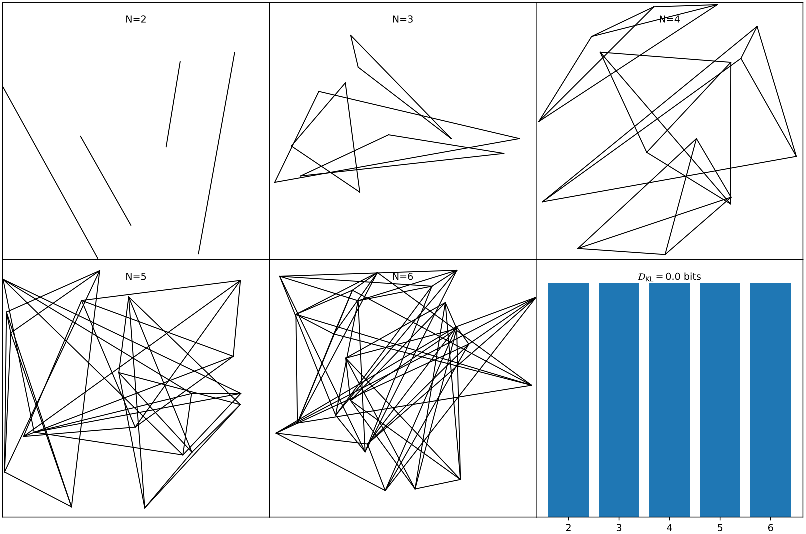
- Extend example so that N can also vary.
- Marginal posterior on $P(N|D)$ (bottom right).
- Instead of plotting posterior *contours*, we plot *samples* from the full posterior distribution.
- Least compressed representation of the posterior.



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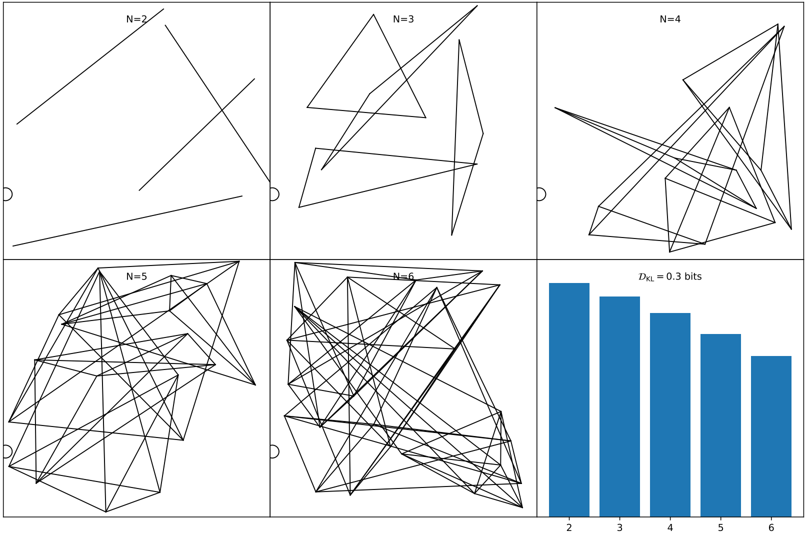

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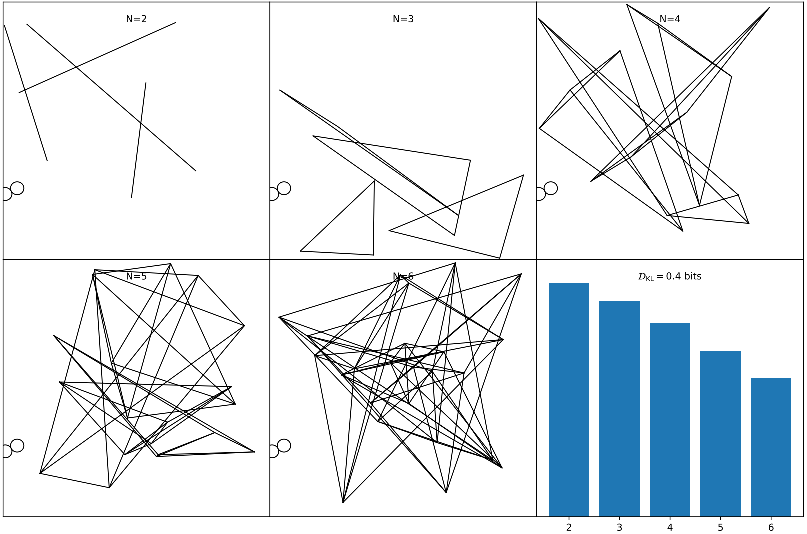

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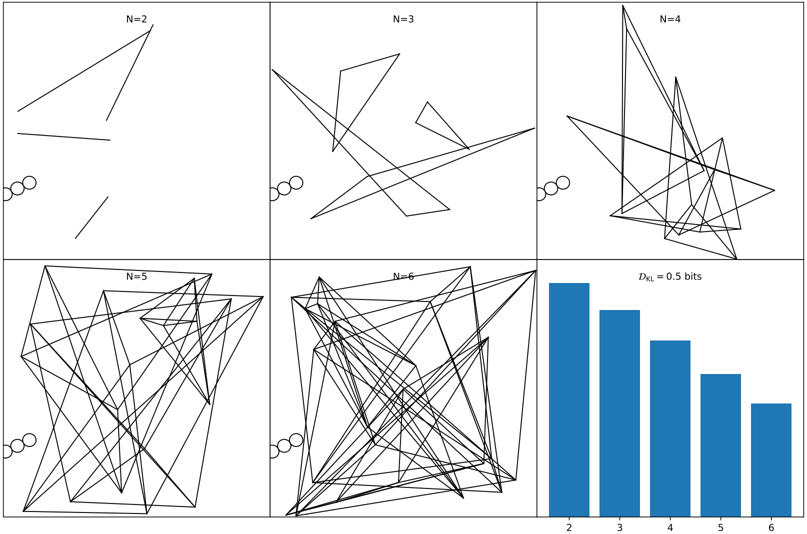

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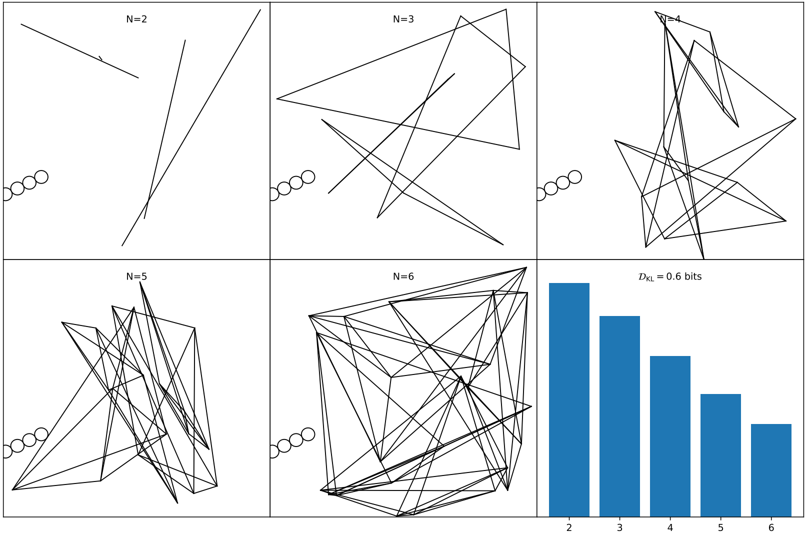

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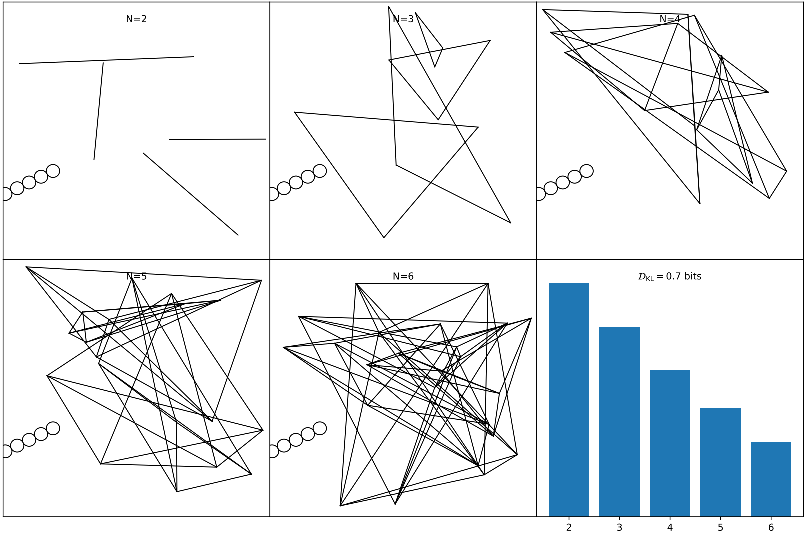

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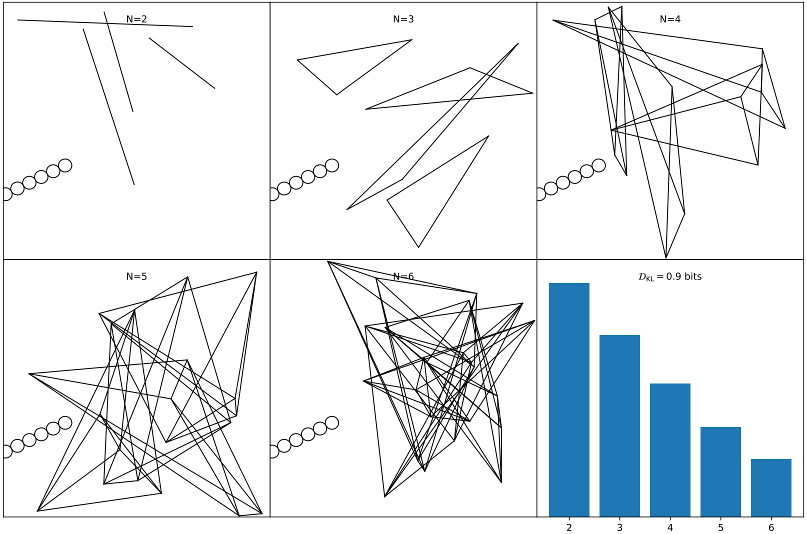

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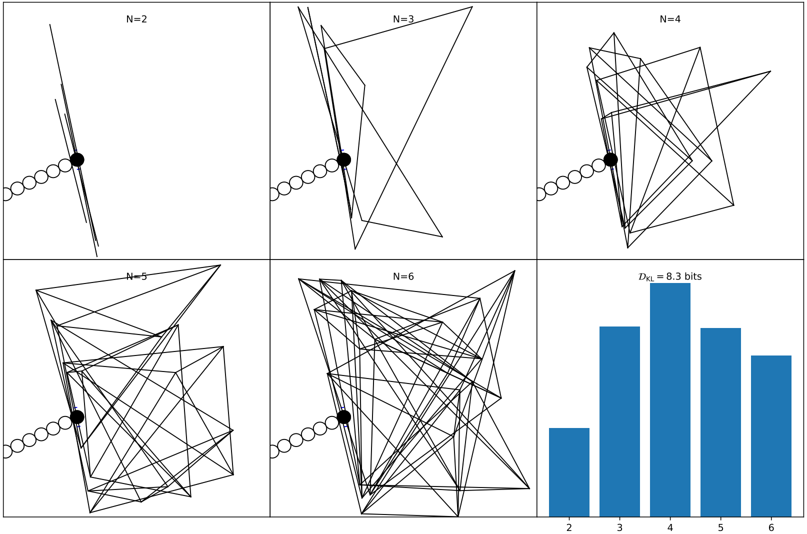

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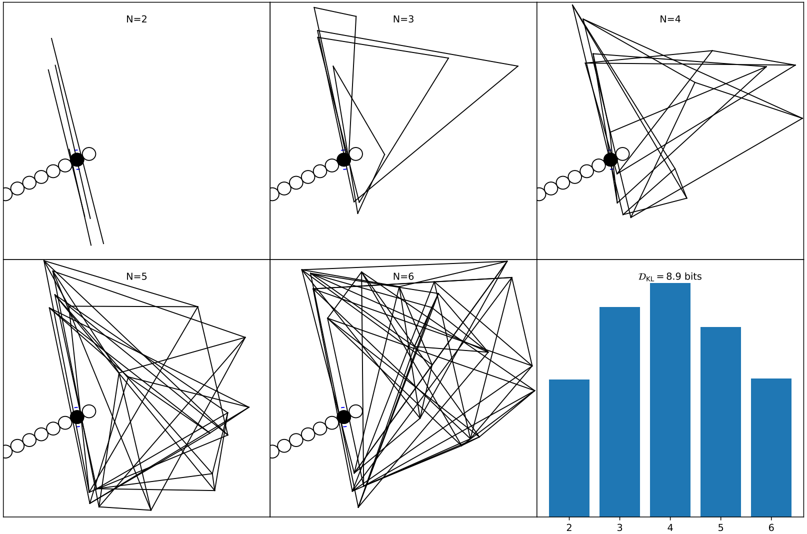

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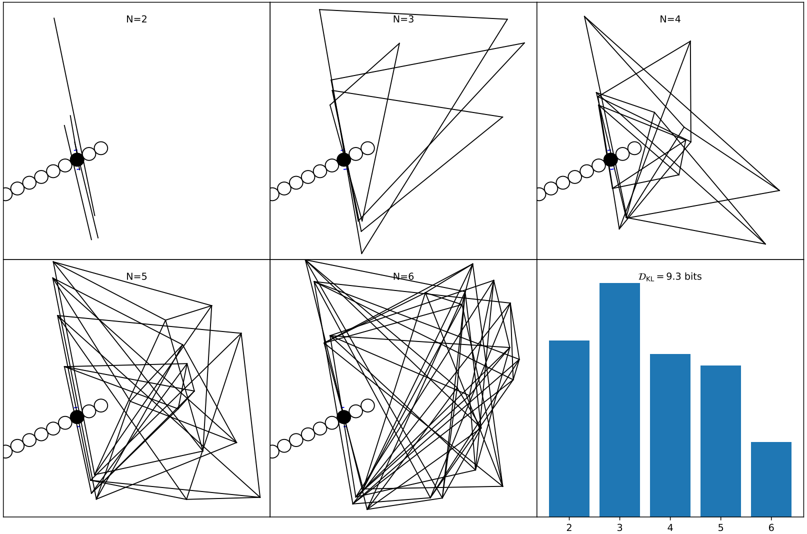

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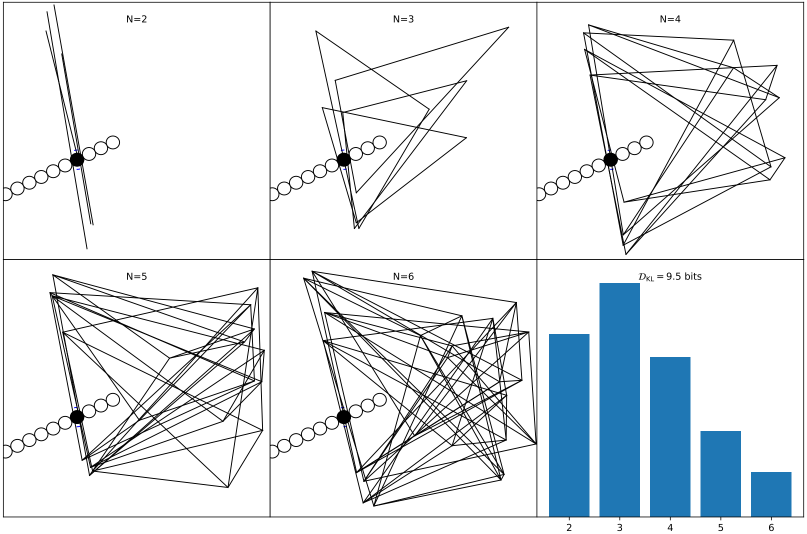

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PolyChord UNIVERSITY OF CAMBRIDGE

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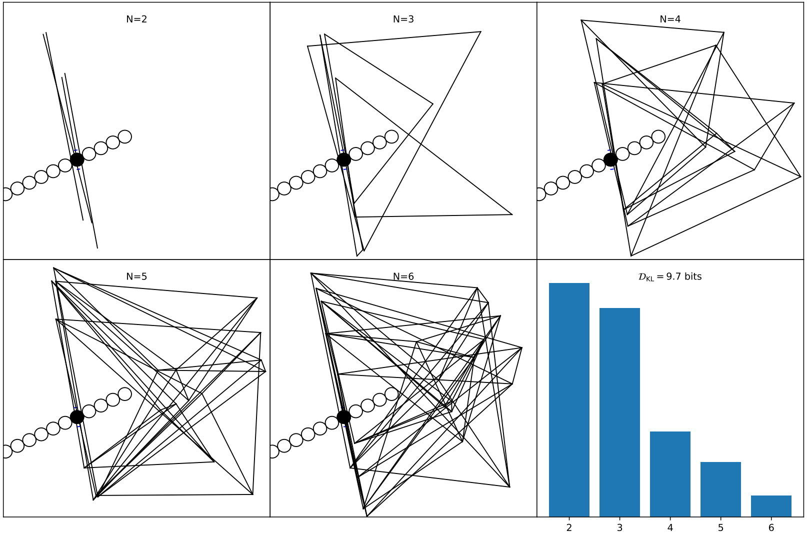

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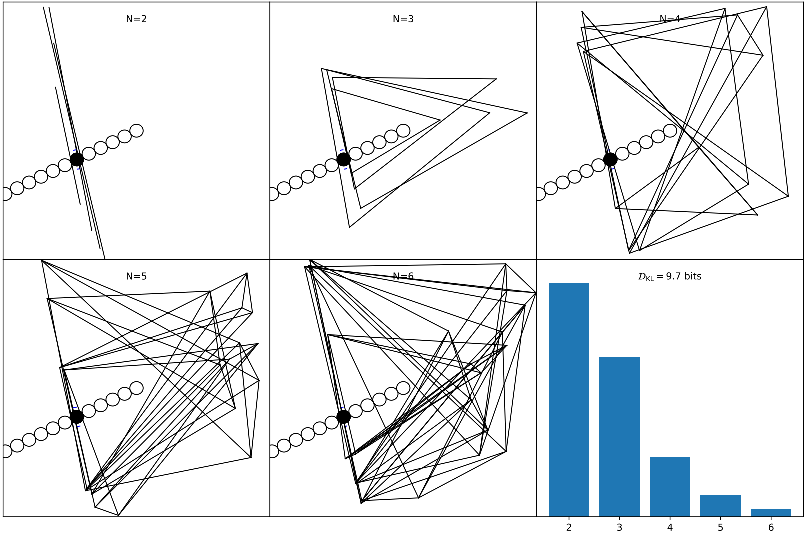

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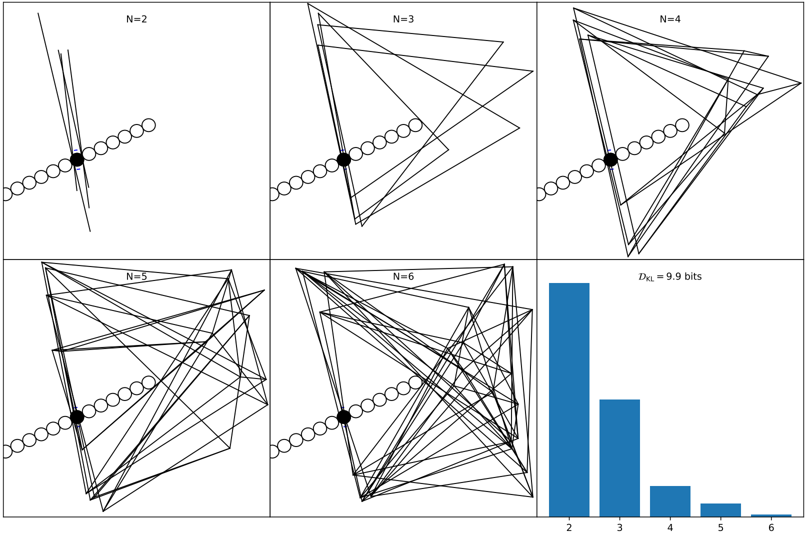

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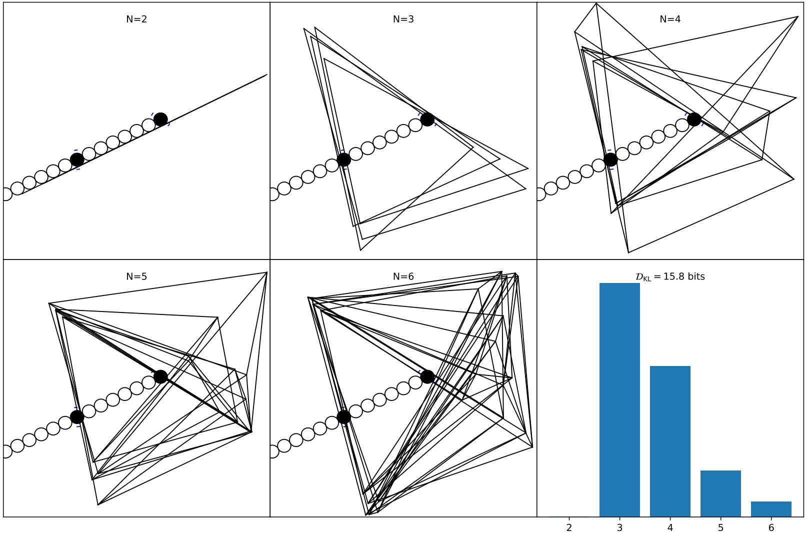

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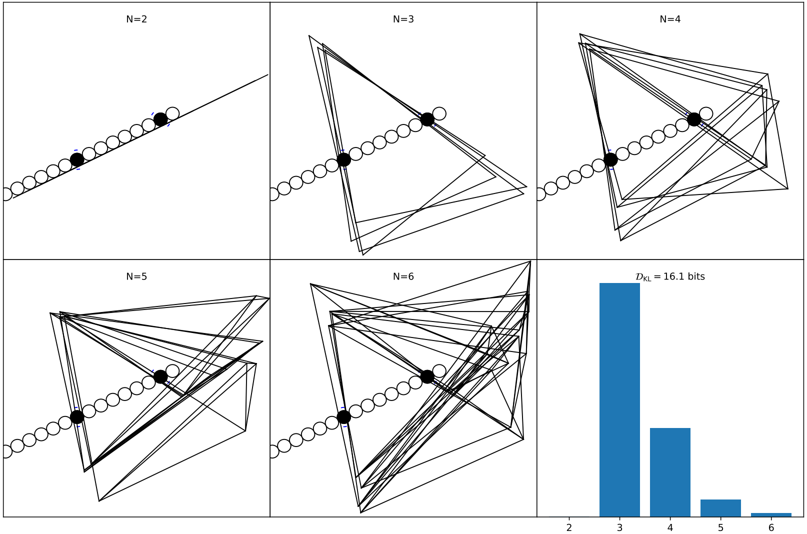

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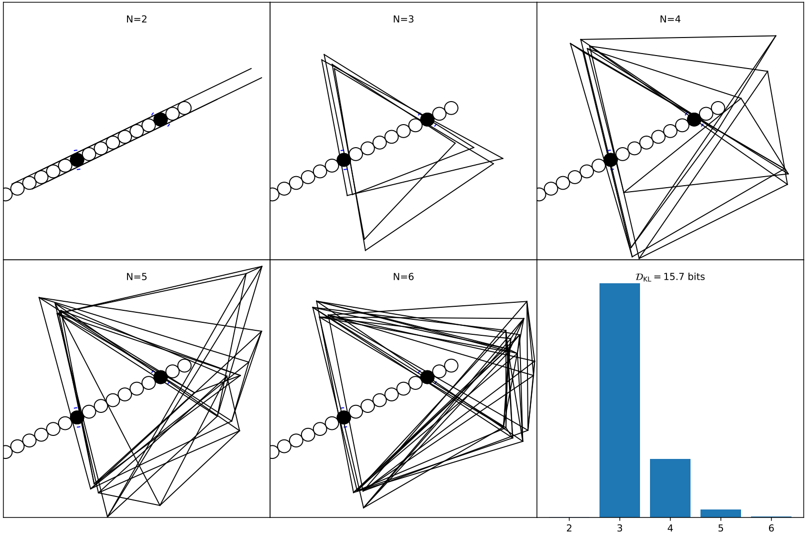

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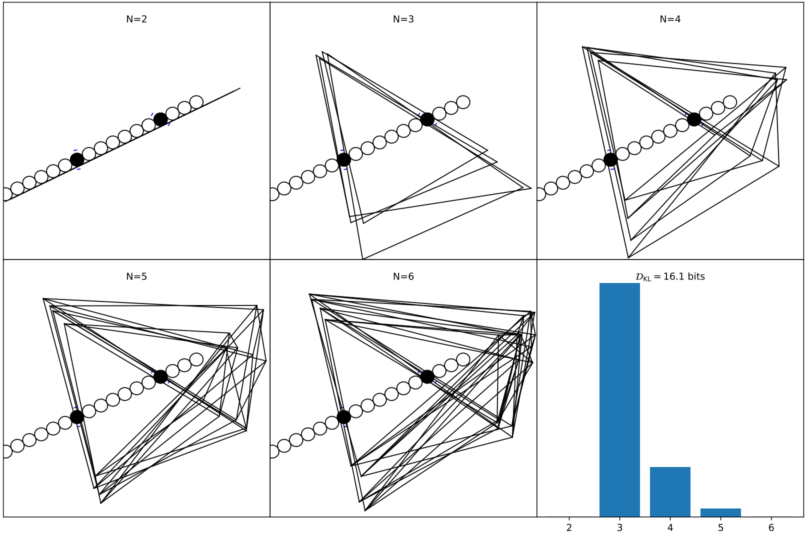

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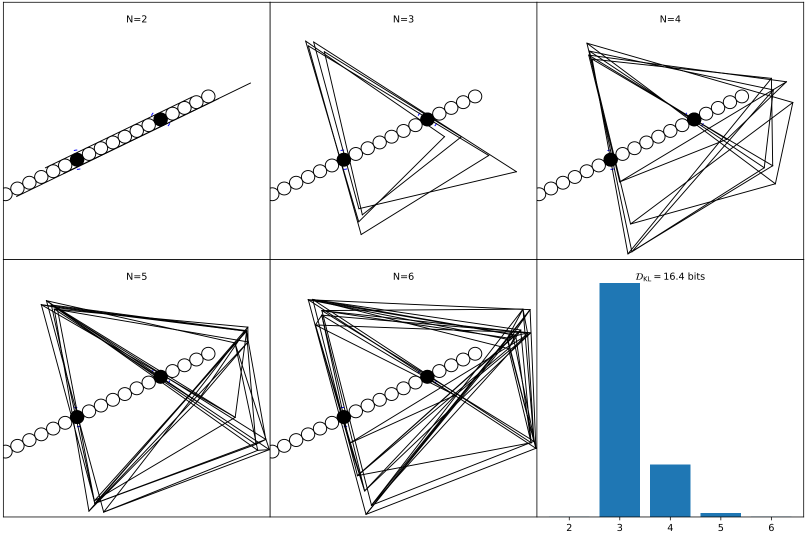

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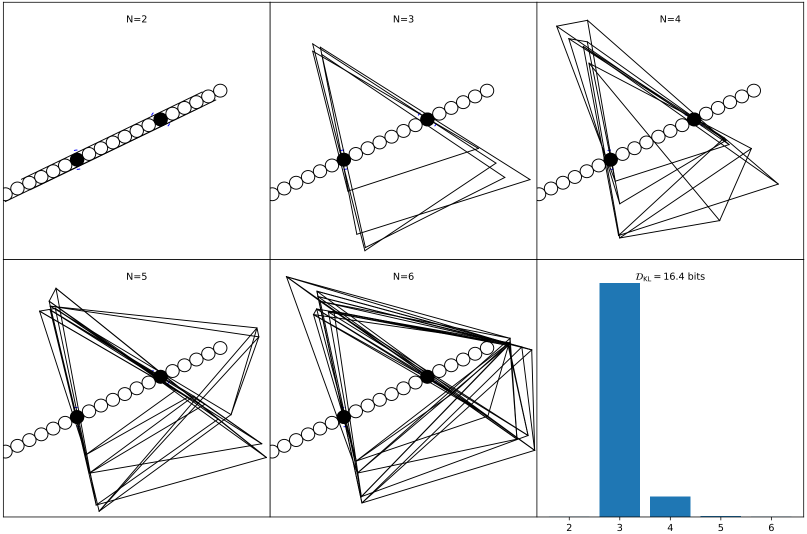

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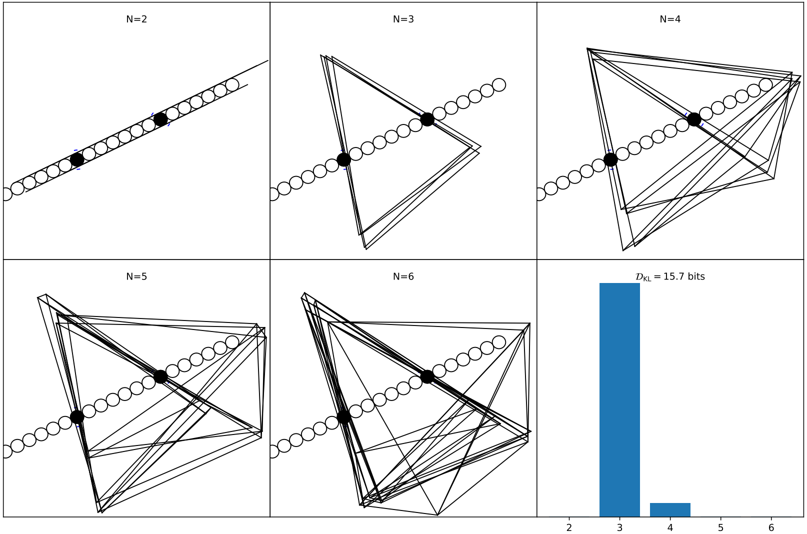

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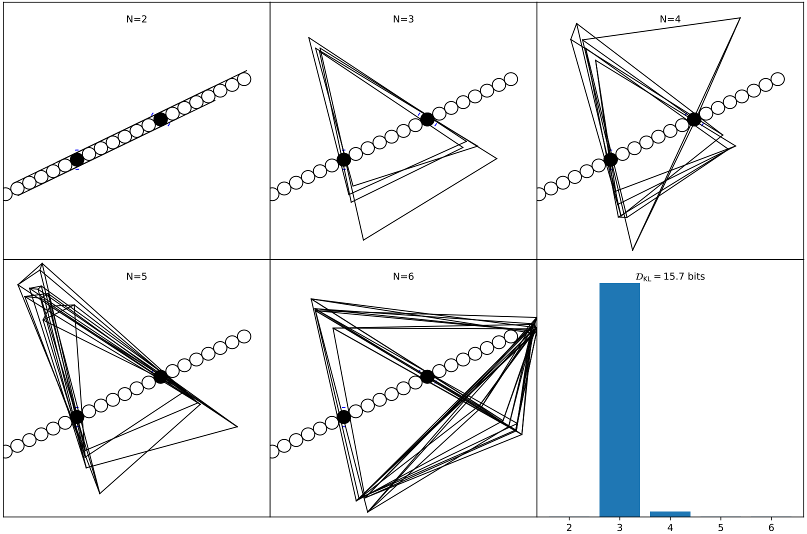

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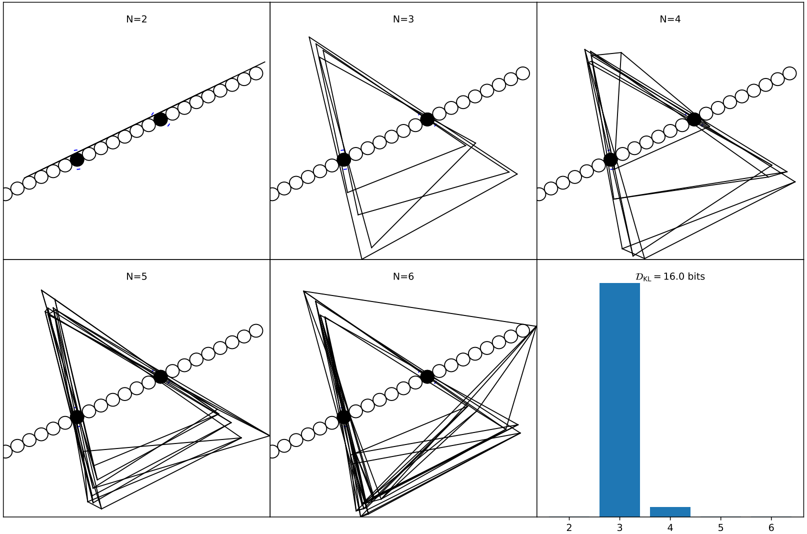

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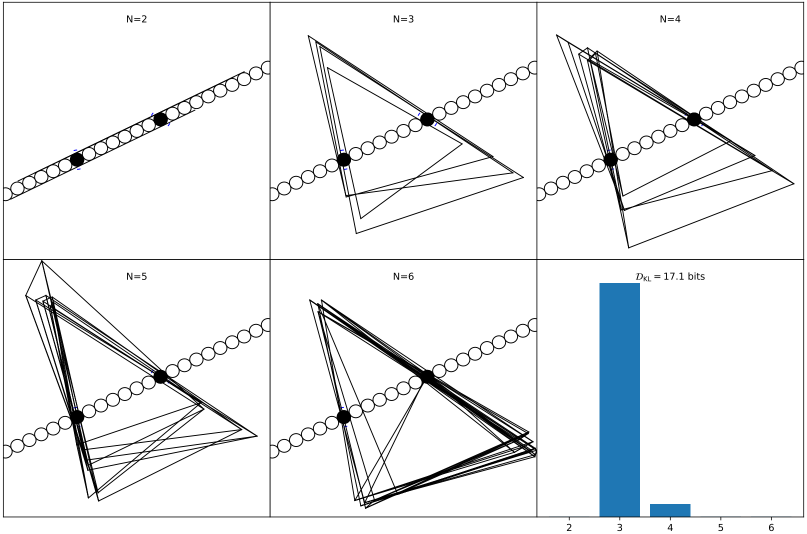

Example 2: Optimising sensor networks (CEME2.3 & CEME4)

- TDOA sensors: blue, orange & green dots
- Transmitter: red cross
- Contours: posterior distributions
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  - combined posterior in red (solid peak)
- Where to put sensors?
- Compute the localisation (information gain $\mathcal{D}_{\mathrm{KL}}$), distributed over all uncertainties:
  - transmitter location,
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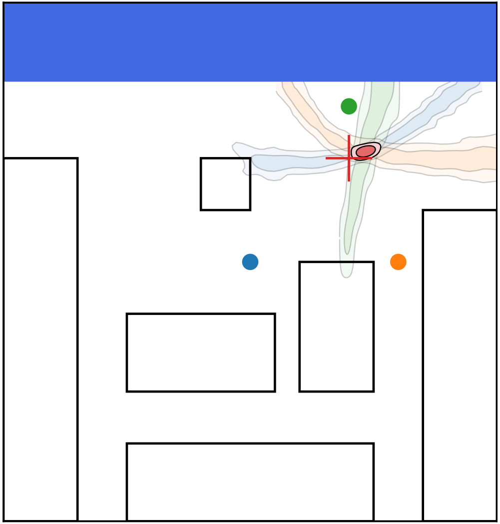
- Find collection of good good solutions
- $\Rightarrow$ nonlinear, nonconvex, ensemble optimisation.



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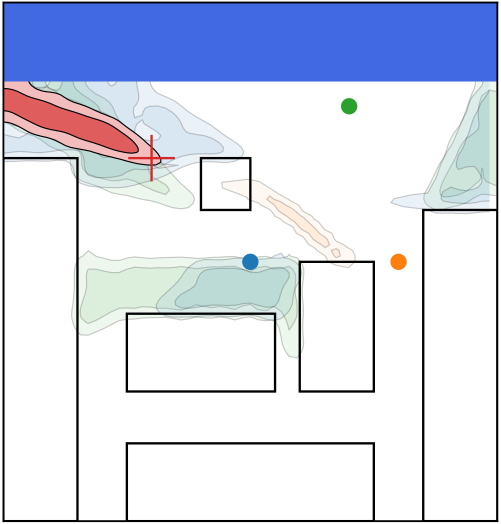

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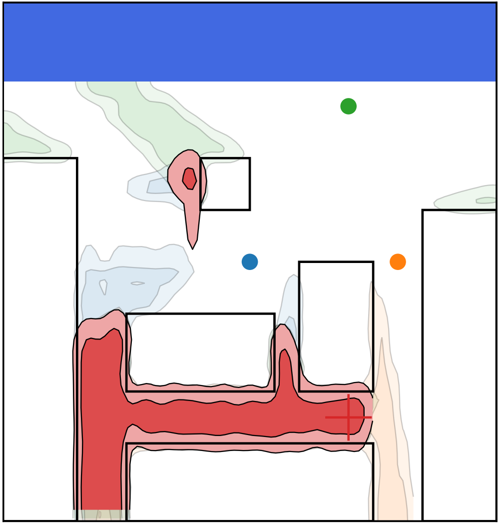

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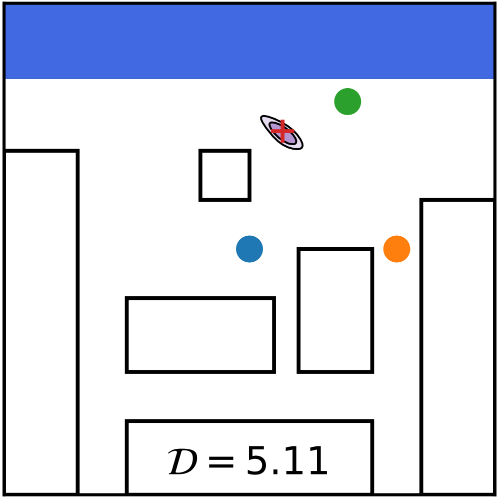

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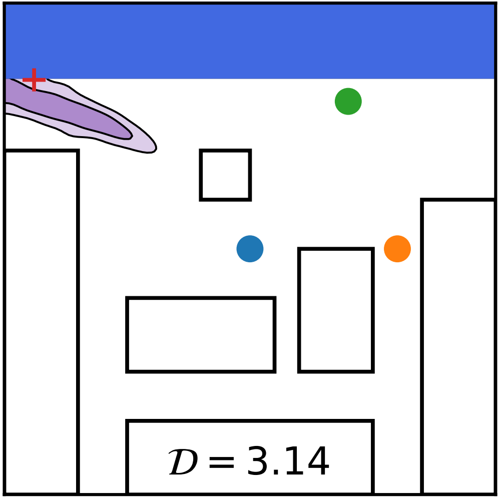

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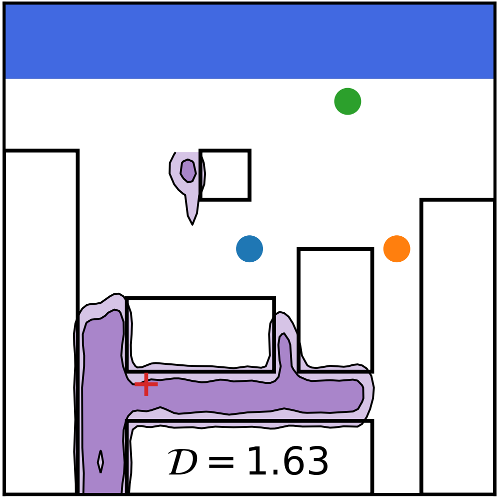

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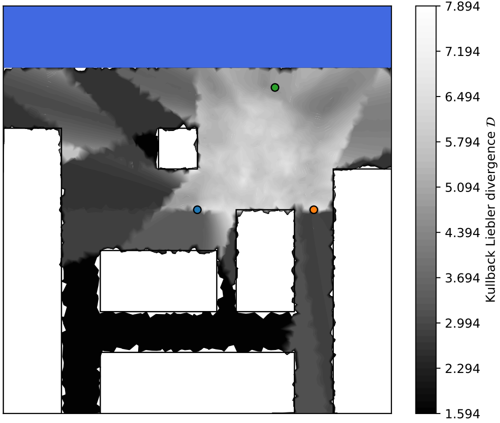

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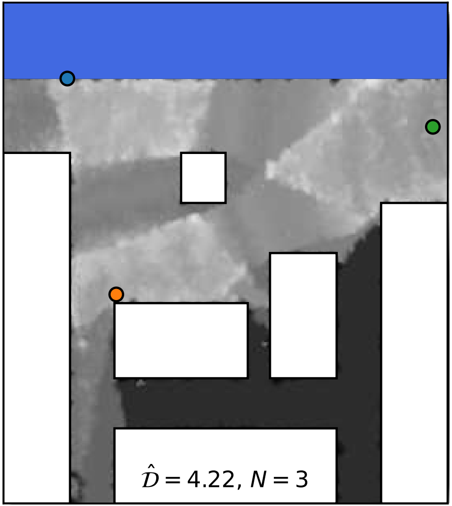

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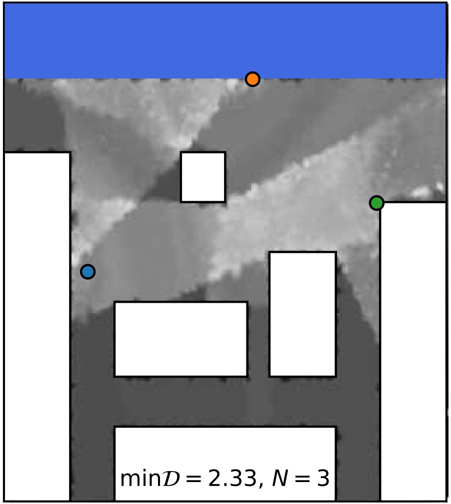

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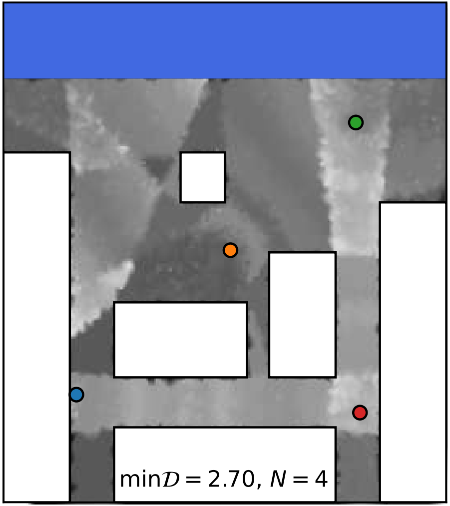

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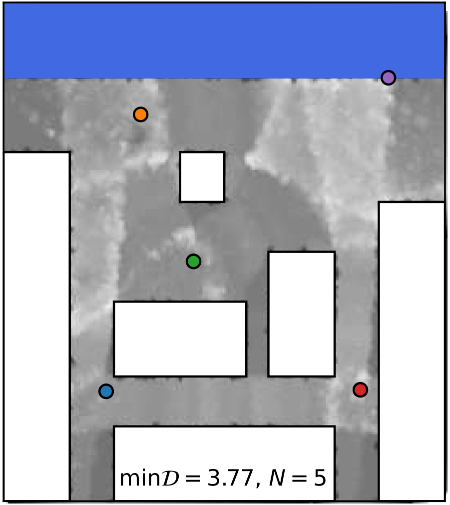

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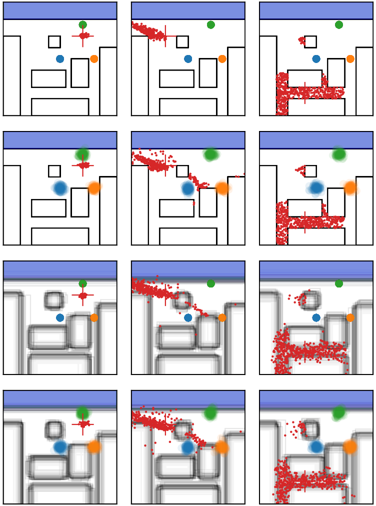
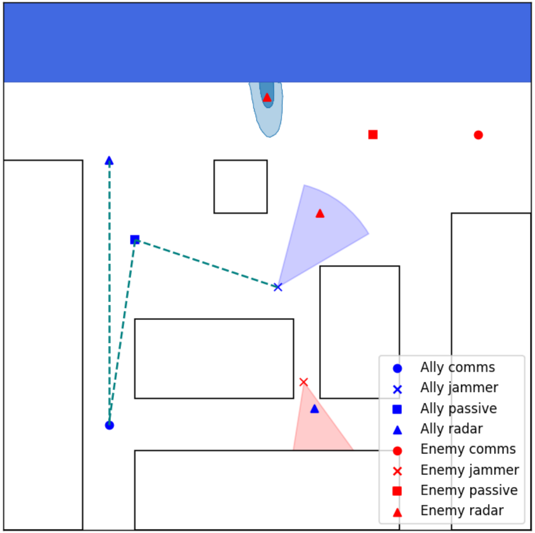
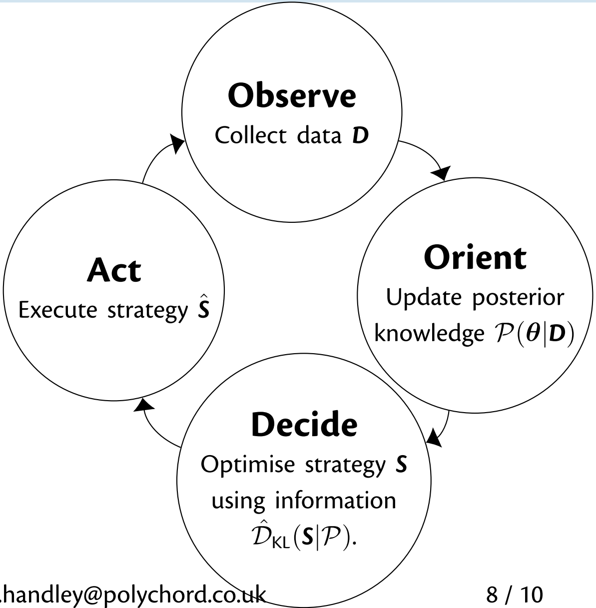


Example 3: MIDAS (CEME6.4)

- MIDAS: Maximum information data acquisition strategies
- Generalise ``best sensor location" to ``best data acquisition strategy"
- Use this to decide what data to take next.
- Add in adversarialism (two competing teams)
- Networks of communicating allied sensors
- Adversarial capacity (jamming)
- Ability re-roll (e.g. UAV) capability
- Use same approach to decide when & how to re-roll.





- Mathematical instantiation of John Boyd's OODA loop.
- Tight coupling between **Bayesian statistics** (updating knowledge) and **Information theory** (how/when to gather more)
- Nested sampling (`PolyChord`) is used at both **Orient** and **Decide** steps, in Bayesian & Optimisation mode.
- However, given that all of these will only ever be *Models* of the real world, the **Act** step will need to be **human-in-the-loop**.

So what?

Current research & future directions

- DSTL+PC/UCAM+PA have shown that Bayesian methods capture natural data fusion at scale.
- We know the complex future EME is going to be too complex for unaugmented humans.
- The missing piece is the **Act** step.
- For **human-in-the-loop** decision-making the rest of the loop needs to present and compress the information in a way that is **actionable** and **explainable**.
- This is the frontier of our current research
  - Designing optimal theoretical system that assists in the decision cycle
  - Giving human agents what they need, when you need it
  - Should get out of the way given human insight

Summary

- Astrostatisticians continue to innovate at the frontier of inference.
- These techniques currently require laptop- to high-performance computing power.
- For generation-after-next techniques, we can assume they will be in our pocket/clothing.
- The Bayesian OODA loop quantifies optimal human-in-the-loop decision-making.
- Science & Technology explored here is not challenge-specific.
- These techniques are complementary to machine learning/AI