Intelligence in Animals and Machines

Navigation

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Learning Outcomes

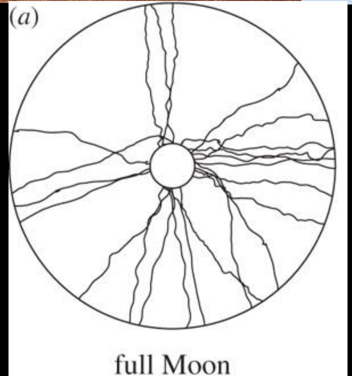
At the end of the lecture, you should be able to:

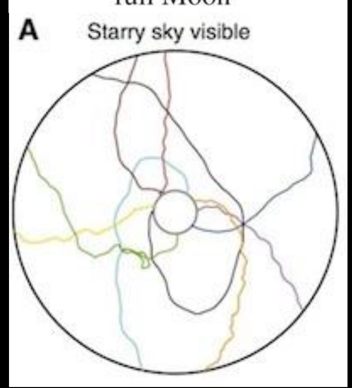
- How navigation is an example of a universal behaviour, where we can see the shared components across species.
- Use insect examples to give a detailed account of navigation components and the way they are influenced by embodiment and situatedness.
- Understand how large brain navigators combine information from different navigational strategies.
- Explain how different classes of robot navigation algorithm depend crucially on sensors, computation speed and situatedness.

Travelling in a straight line is hard

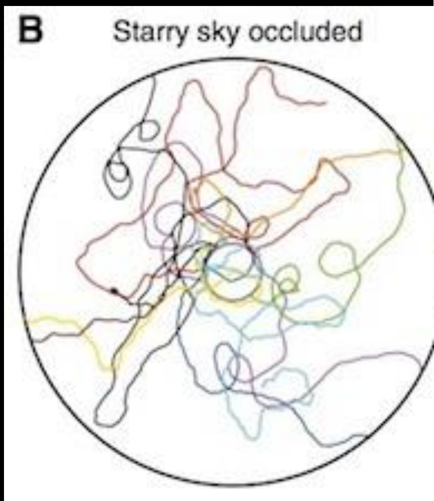
Nocturnal dung beetles need to get away from a dung pile as quickly as possible to stop other beetles stealing their dung

This means they are adapted for rolling their dung balls in a straight line



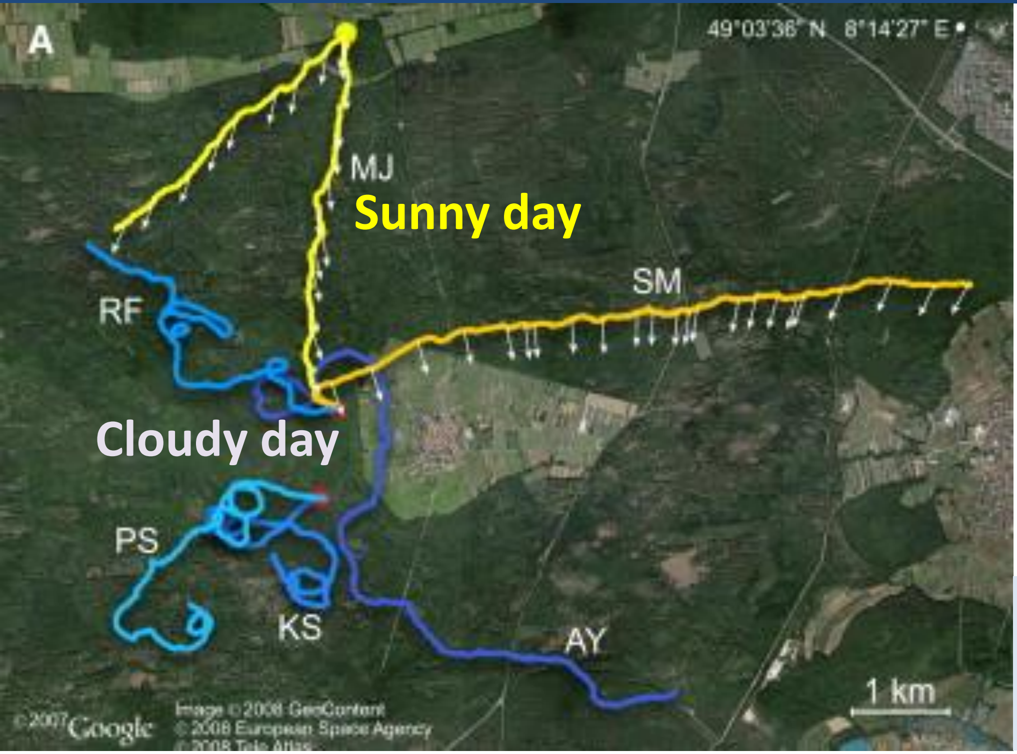


- If external cues (ie objects eg Moon or bright light) are present get straight paths
- Even the pattern of stars works (but better cues = straighter paths)
- However without external cues paths are not straight



Dacke et al (2013) Curr Biol

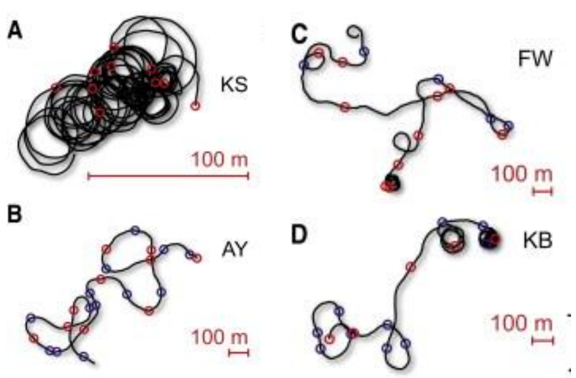
Travelling in a straight line is hard for humans



Souman et al (2009) Curr Biol

- People were asked to walk in a straight line in forest (so can't aim for mountain in the distance)
- Yellow paths are 3 people when it was sunny
- Blue paths are 3 people from a cloudy day

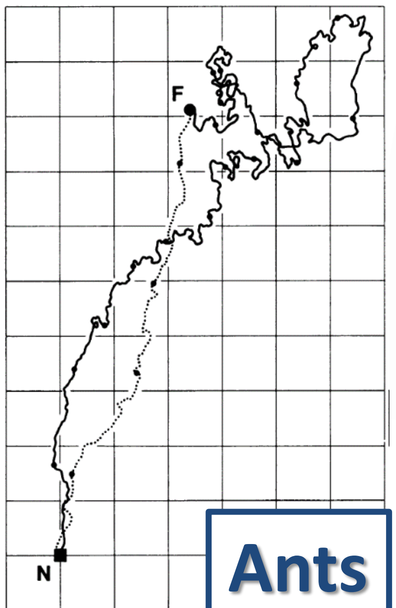
Humans also need external cues for straight line walking



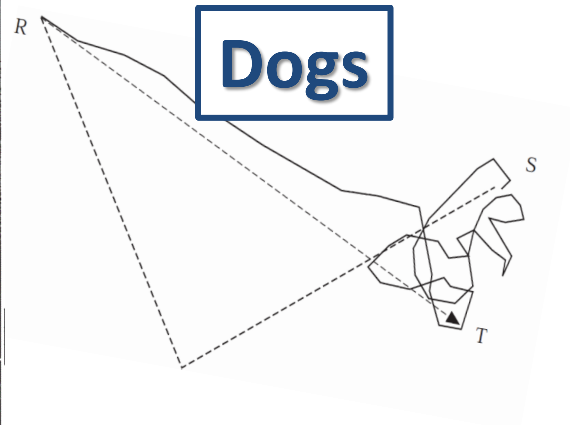
- Attempts to walk in a straight line with no vision (eyes covered) also shows we need external cues
- Why didn't they use non-visual cues such as wind?
- "I couldn't use the direction of the wind as it kept changing"
- did not realise this was as *they* changed direction

We all have the same toolkit.

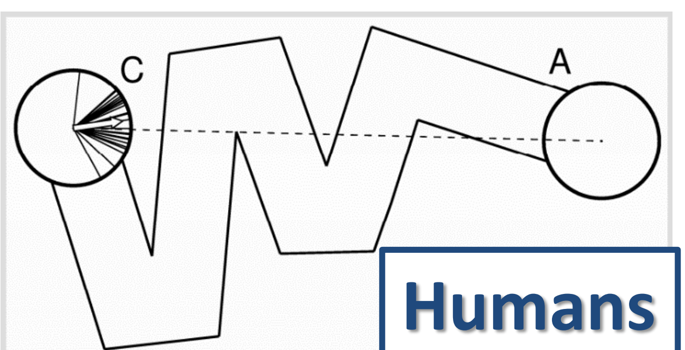
Sense of direction



Ants

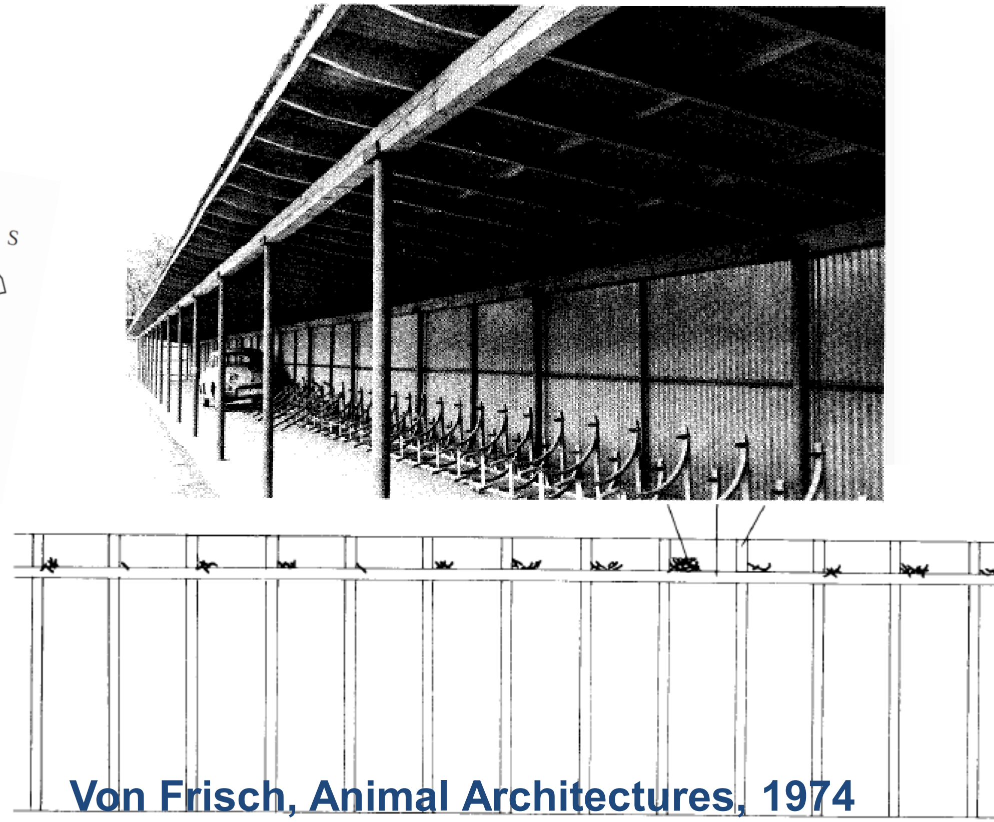


Dogs



Humans

Learning



Von Frisch, Animal Architectures, 1974

1. Insect navigation?

- Why study navigation?
  - Task easy to define and behaviour is precise
  - Performance easy to measure and theoretical models can be tested
  - Universal behaviour
- Why study insect navigation?
  - Looking for phylogenetically widespread building blocks of spatial cognition
  - Social insect foragers in particular are navigation experts

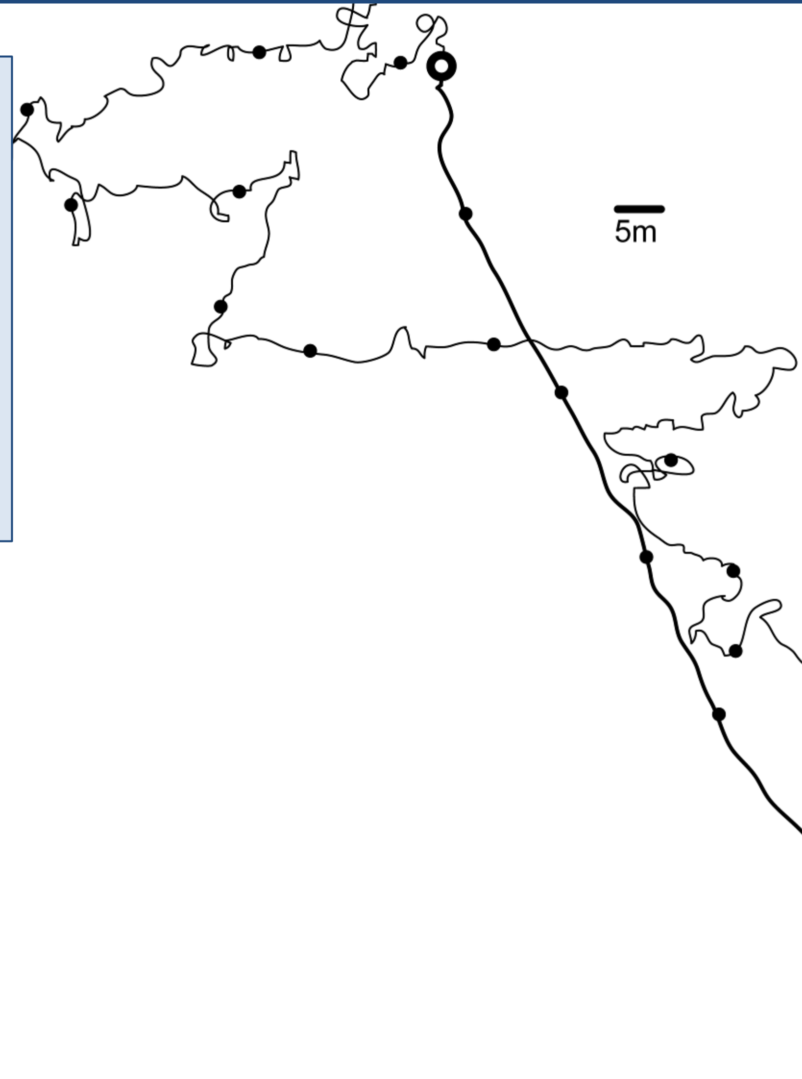
Cataglyphis bicolor

Apis mellifera

Melophorus bagoti

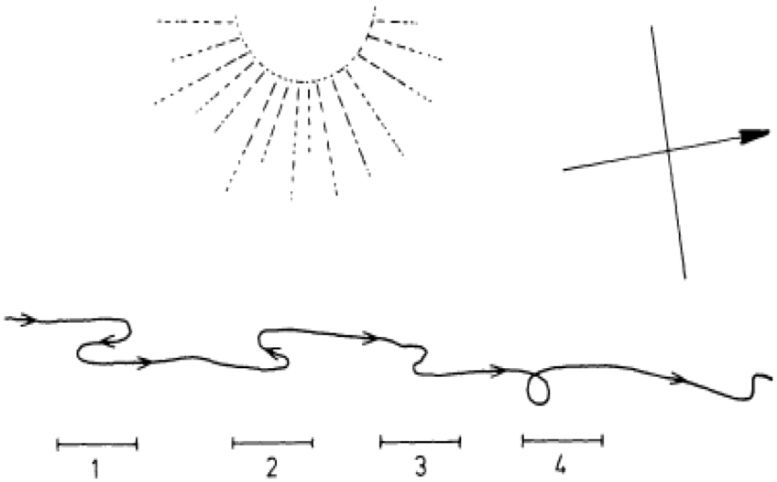
Path Integration

PI allows an animal to encode its co-ordinates relative to its nest and so go home along a direct path without prior knowledge of the terrain

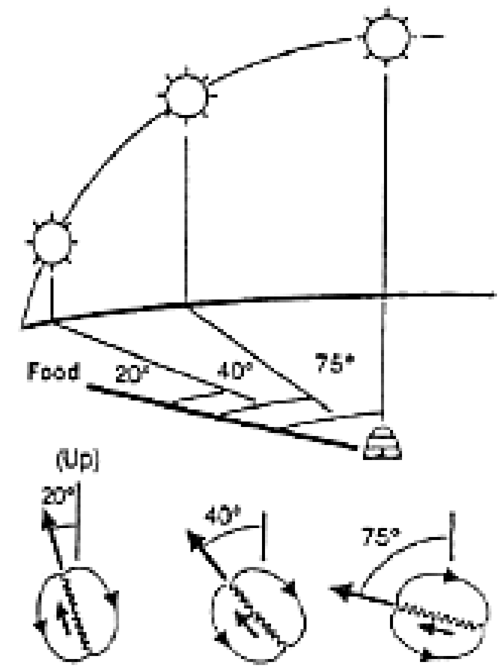


Wehner and Wehner 1992

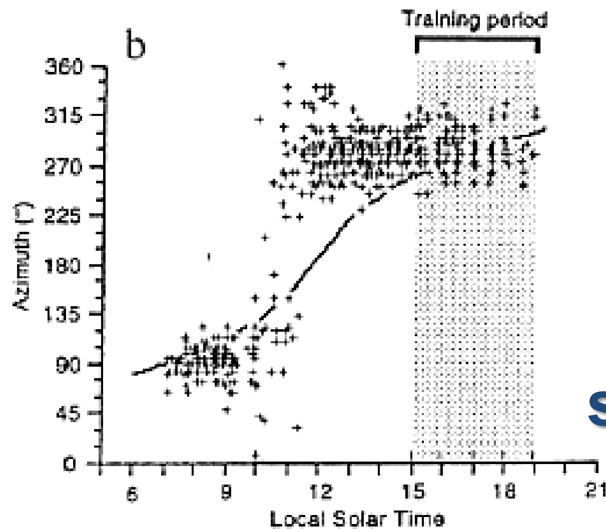
Ants and bees use the sun for direction information



Sun as a reference



Sun compass

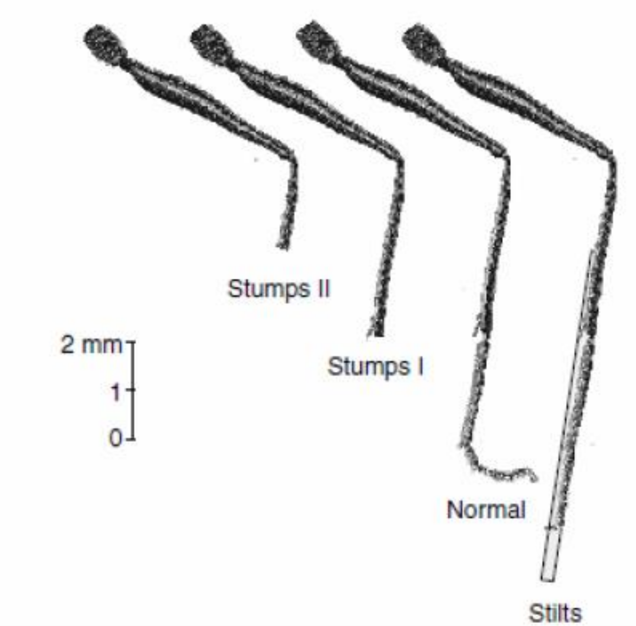


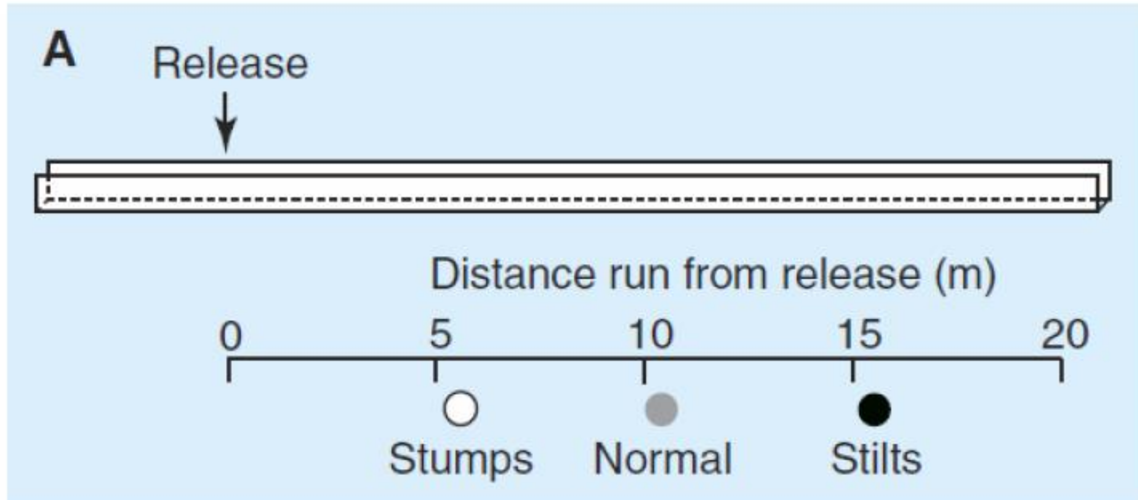
Innate knowledge of sun movement

Dyer and Dickinson (1996)

Santschi (1923)

PI needs distance information - ants

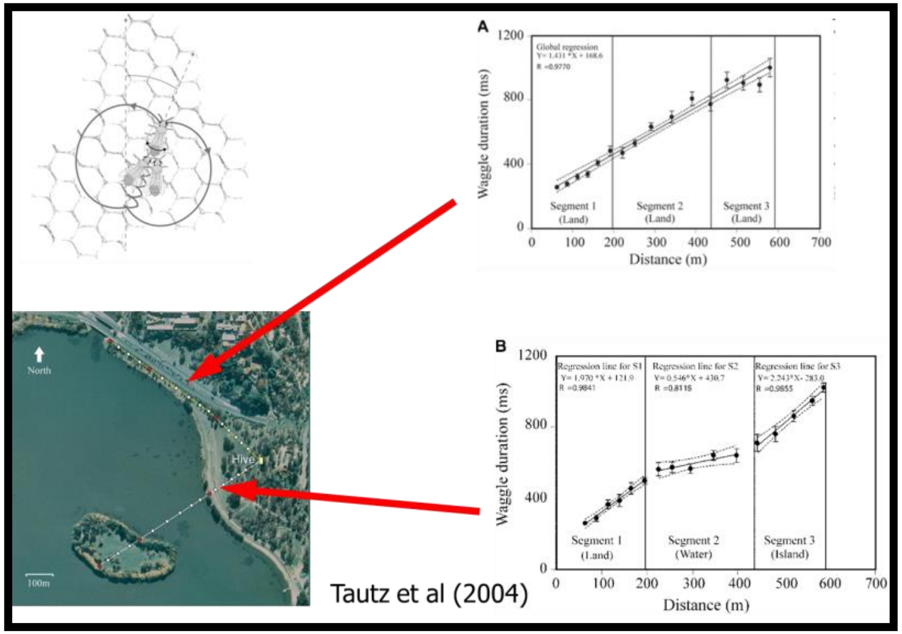




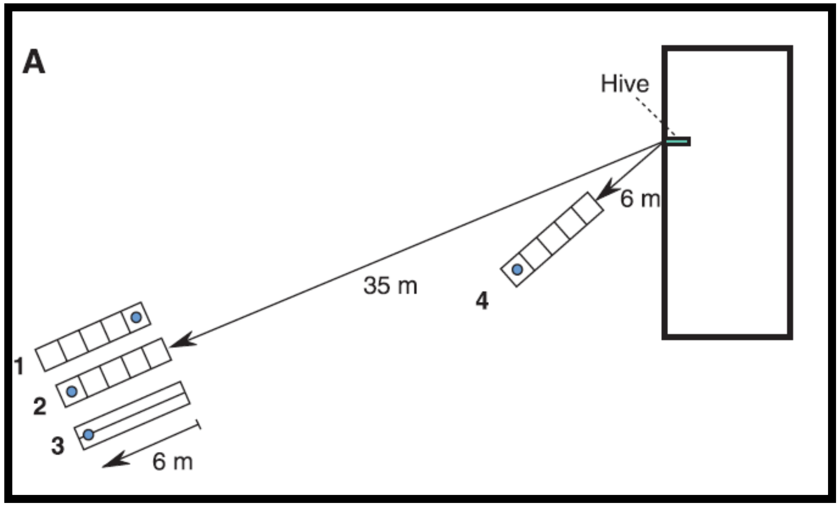
Altering the length of their legs changes the distance that they run, showing that they integrate the number and length of strides.

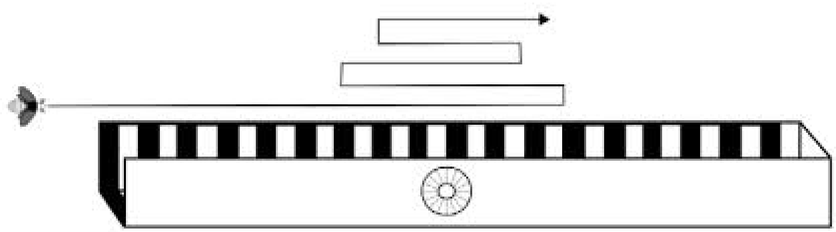
Wittlinger et al (2006)

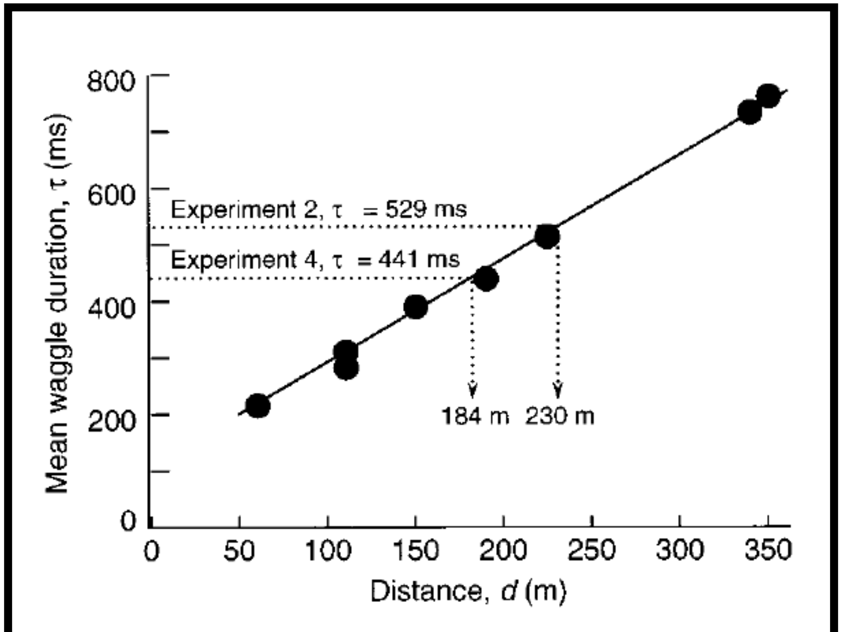
PI needs distance information - bees



Tautz et al (2004)







Srinivasan et al (2000)

How sensory ecology influences distance measuring

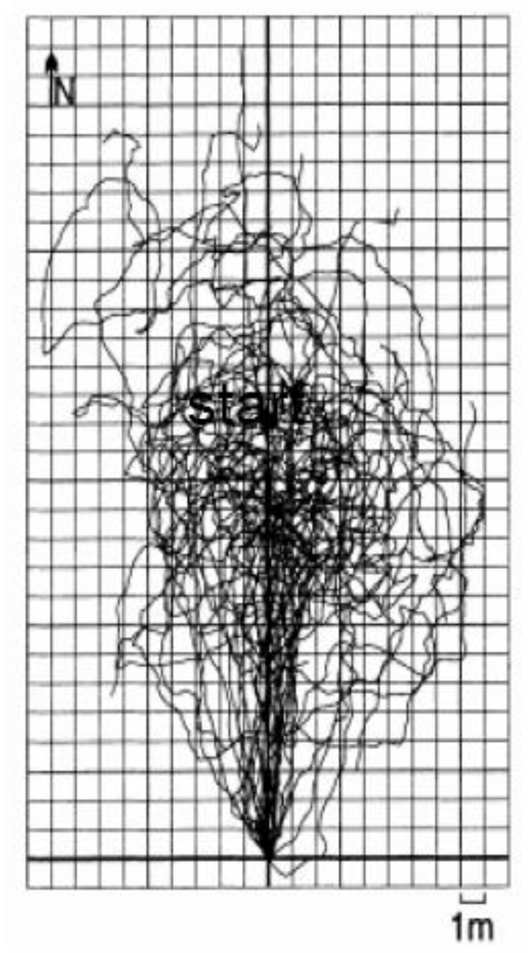
- **Measuring distance on the ground and in the air.**

- A walking insect can monitor its leg movements to measure distance.

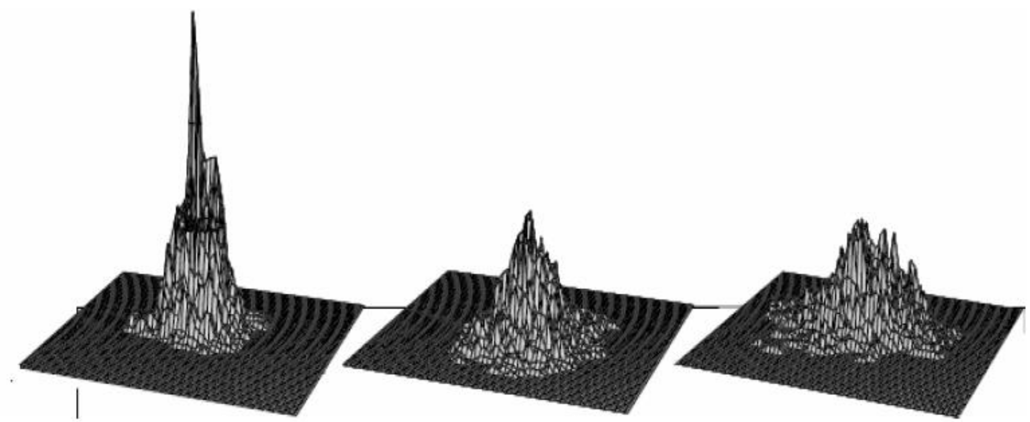
- Uncertain winds mean that a flying insect cannot rely on motor output. It has to rely on 'optic flow'.

- Optic flow derived distance information doesn't have to be accurate – as long as individuals fly through same environment.

Errors of Path Integration



Path Integration has errors of distance and direction



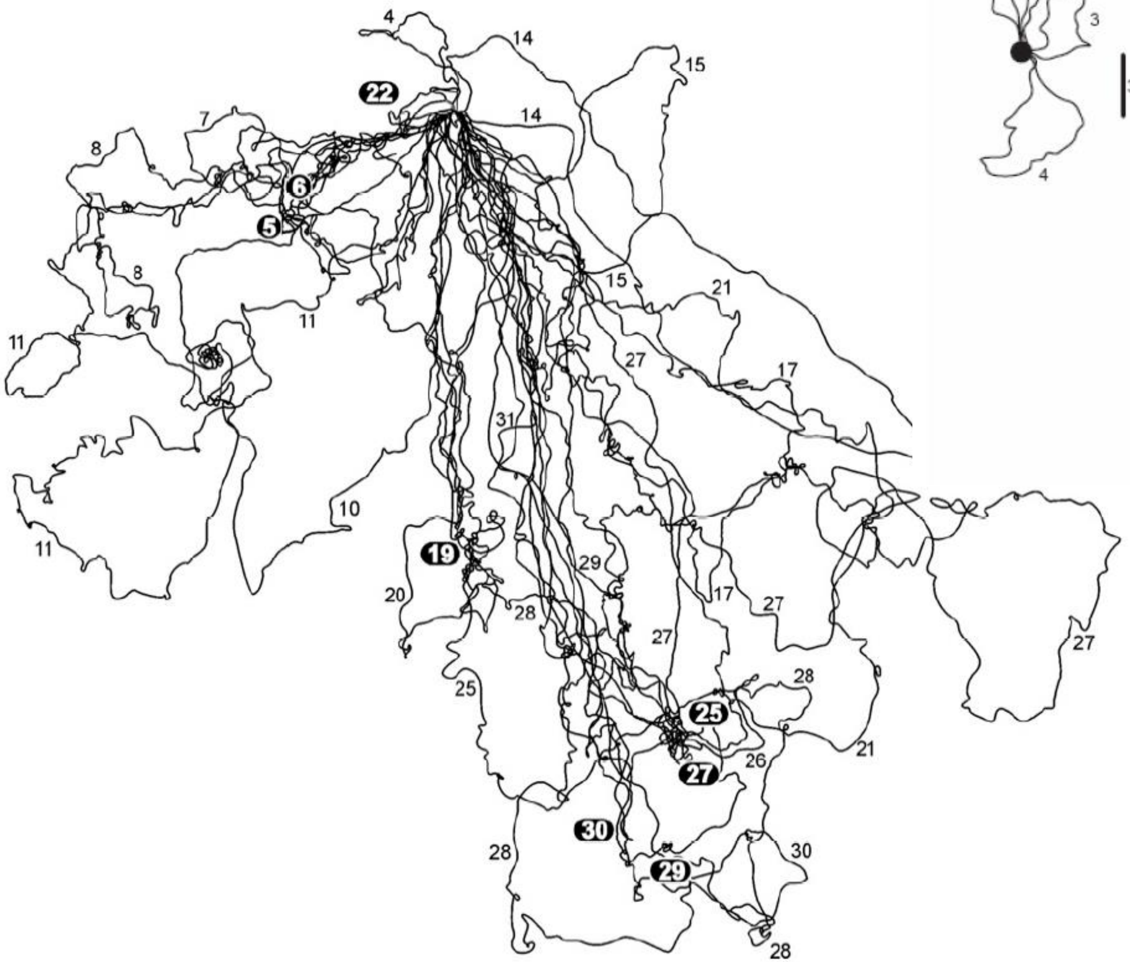
Wolf and Wehner

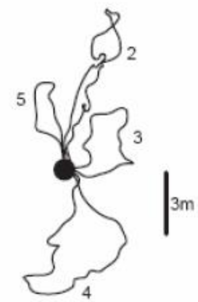
Merkle and Wehner

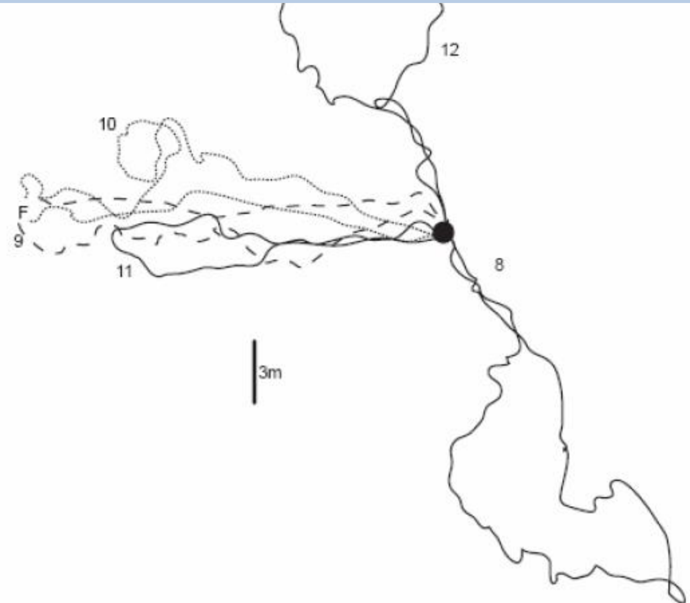
Natural Route Learning

To mitigate errors, ants learn routes.

Wehner, Meier and Zollikofer



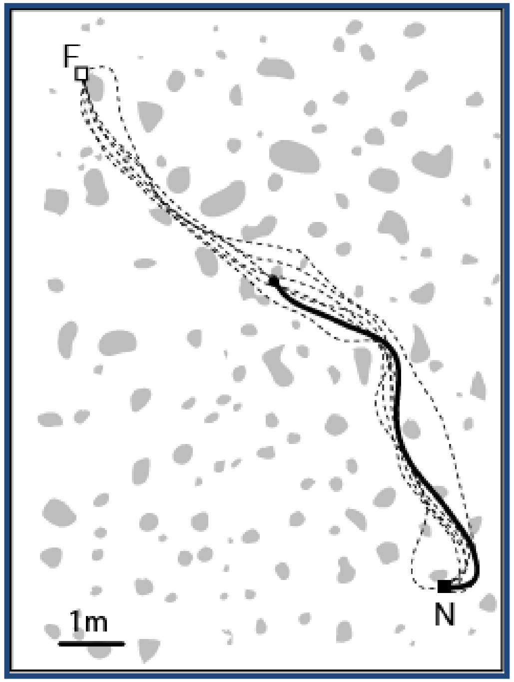


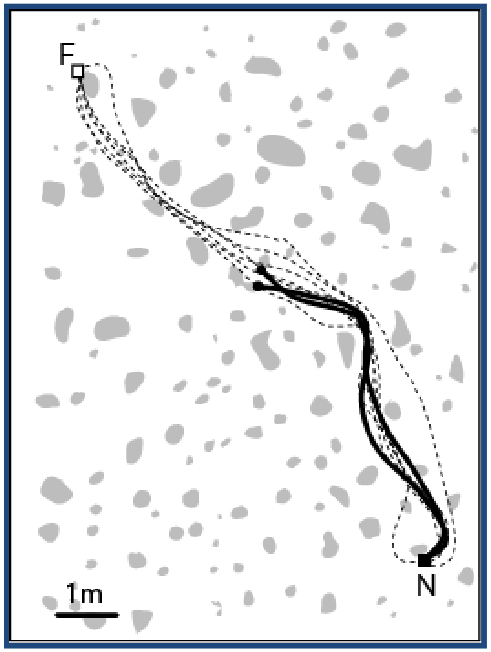


Mature routes

- **Experienced foragers demonstrate world knowledge through idiosyncratic and stable routes that are:**
  - **Independent of Path Integration**
  - **Not reliant on a learnt sequence of behaviours**

Taken from nest



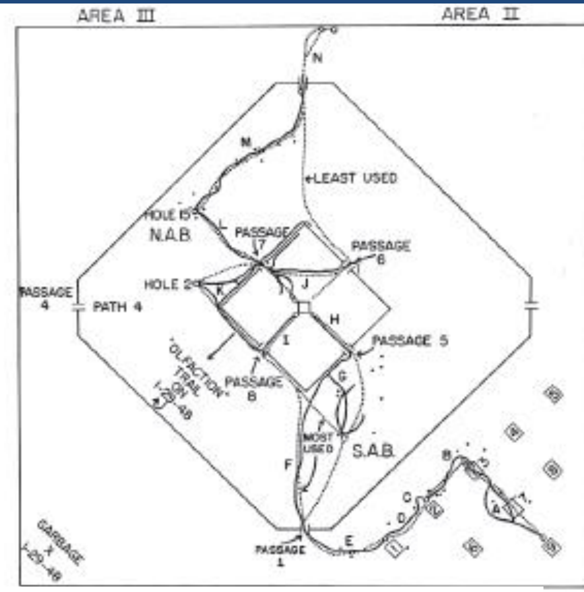


Taken from feeder

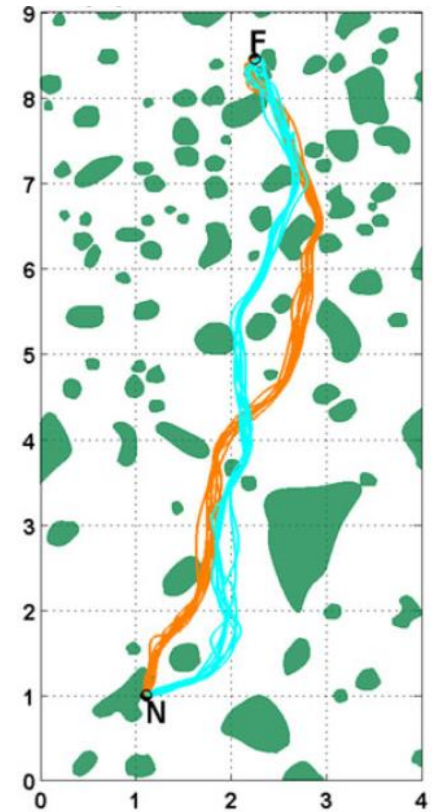
Kohler and Wehner

We are all creatures of habit?

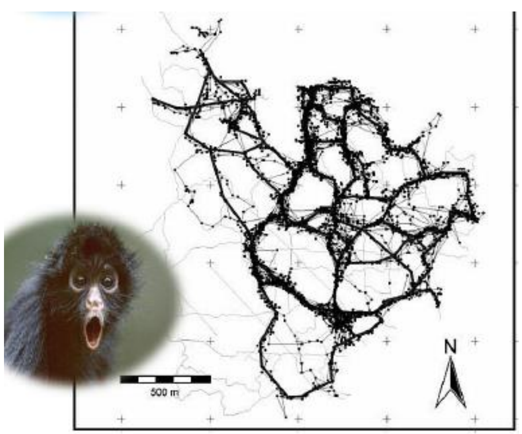
Pigeons
(Biro et al., 2004)



Rats
(Calhoun, 1963)



Ants
(Mangan and Webb, 2012)



Monkeys
(Di Fiore and Suarez 2007)

Humans
(Dee, 2005)

Story so far

- Study of insects has given us the most detailed insights into how navigational strategies – in this case path integration and route learning – can work together.
- Innate strategies allow exploration, then individuals can learn environmental information which is more accurate.
- This leads to idiosyncratic habitual routes – which is a universal strategy across the animal kingdom.

MINI BREAK

Navigation by image matching

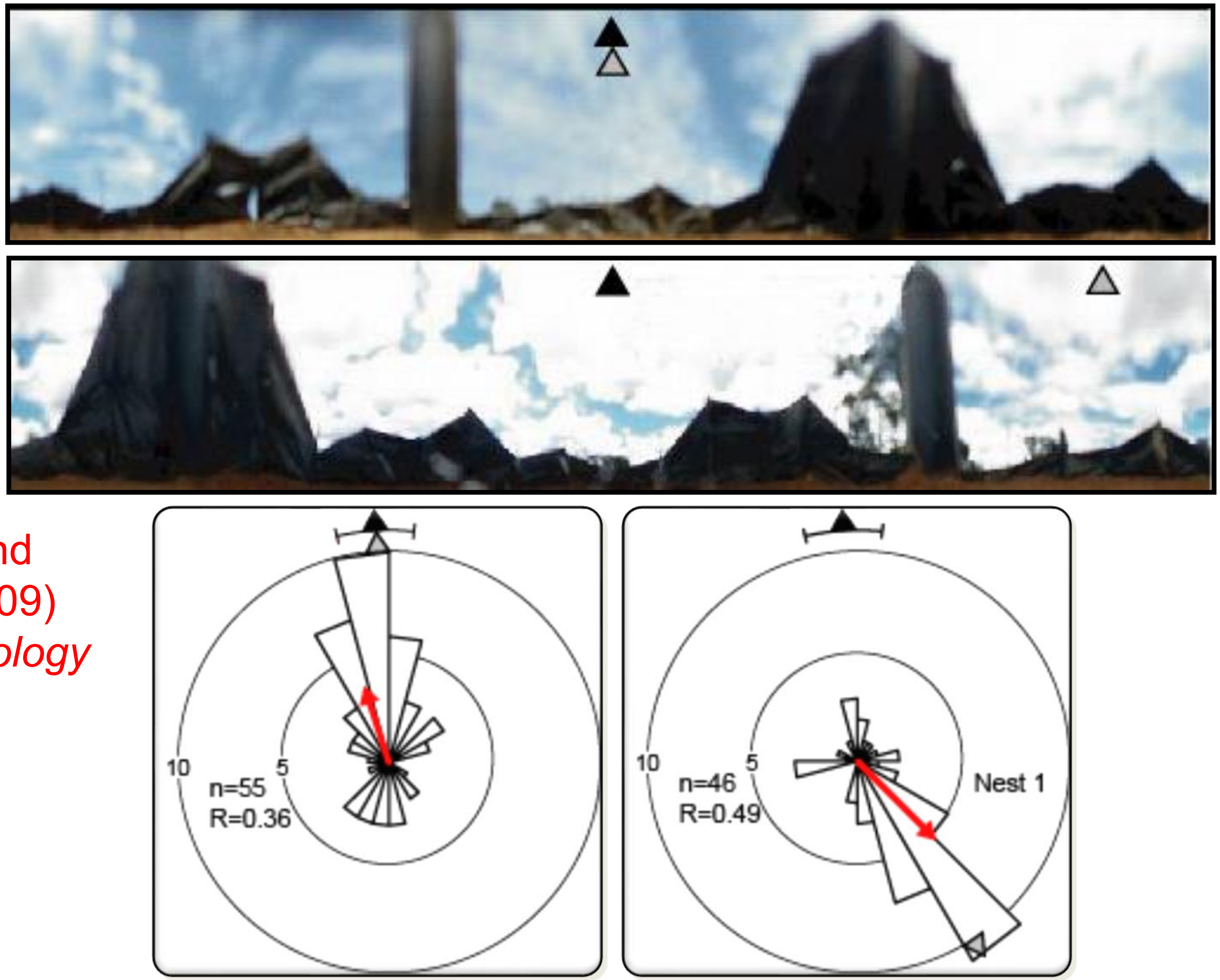
What information guides routes?

What does the world look like to an ant?

Graham and Cheng (2009) *Current Biology*

- Ant-eye view is low-resolution but wide-field (ie sees almost all way round (See Wystrach et al. JCPA, 2016 for analysis
- Can re-create only height of objects above horizon: *panorama*

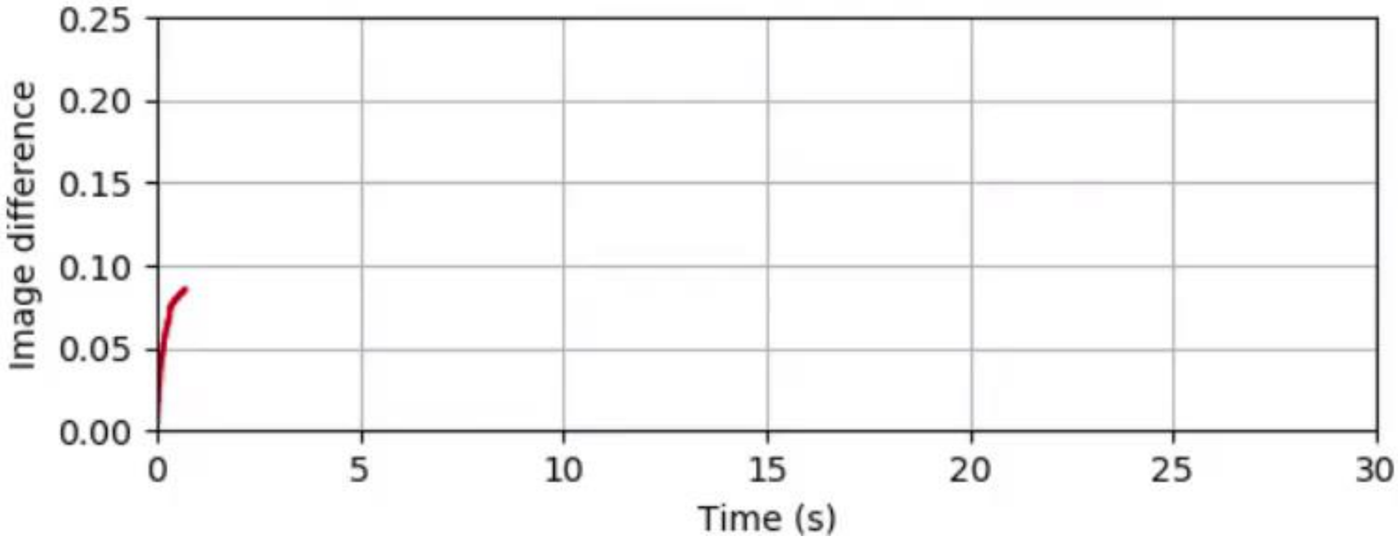
Ants navigate with info from crude panoramas



Graham and Cheng (2009) *Current Biology*

More analysis: Philippides et al, J. Exp Biol, 2011; Wystrach et al. JCPA 2016

Why is that information sufficient? Image differences change smoothly with translation but also **rotation**

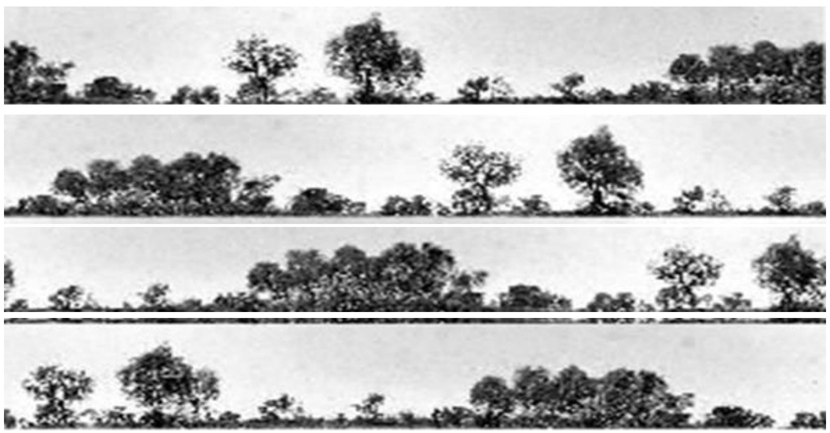


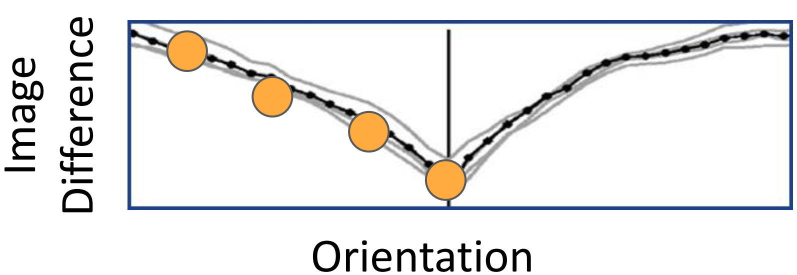
- Navigation by image-matching: move to make view match memory. Snapshot homing
- As views change smoothly, follow image difference gradient (Zeil, 2003)

Visual compass: Use views to recall actions not places

Stored view

Scanned views





Wystrach et al, 2014

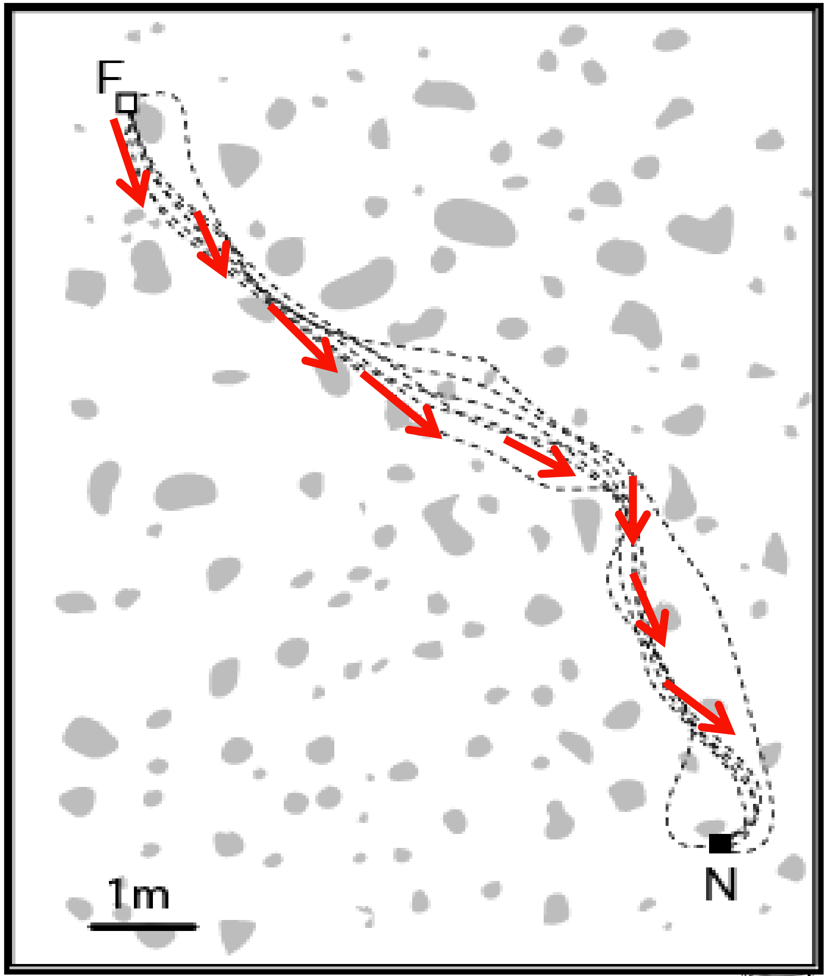
Chains of actions -> Simple route learning

- Task: Travel route once; learn information for navigation (training data for ANN)
- In robotics: Visual Teach and repeat.

- Behaviour (PI) and embodiment means learning views = learning actions
- Learn views as they appear
- In AI terms: behaviour has labelled data

Learning actions has important implications
- Near positions recall similar actions
- Learn continuously; identity of matched view unimportant (ie no location cf maps)

- Train ANN to learn training-route views
- As view ID unimportant train for familiarity NOT recognition
- Navigation without knowing where you are

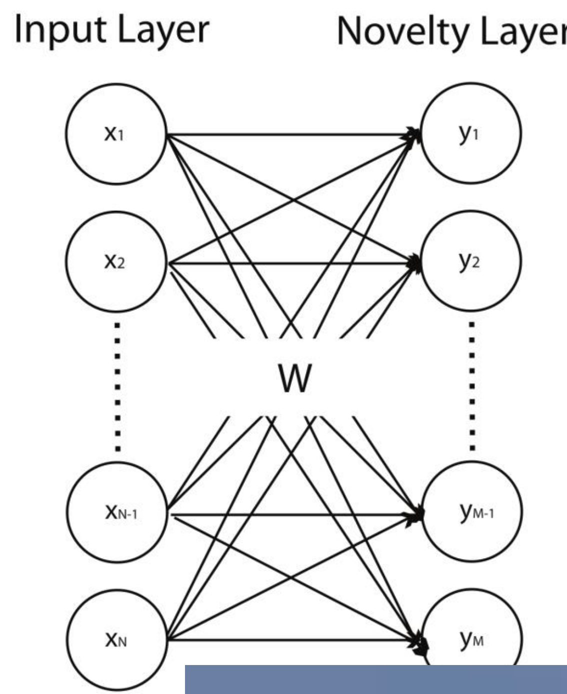


Familiarity-based route navigation

Navigate along a path (using PI)

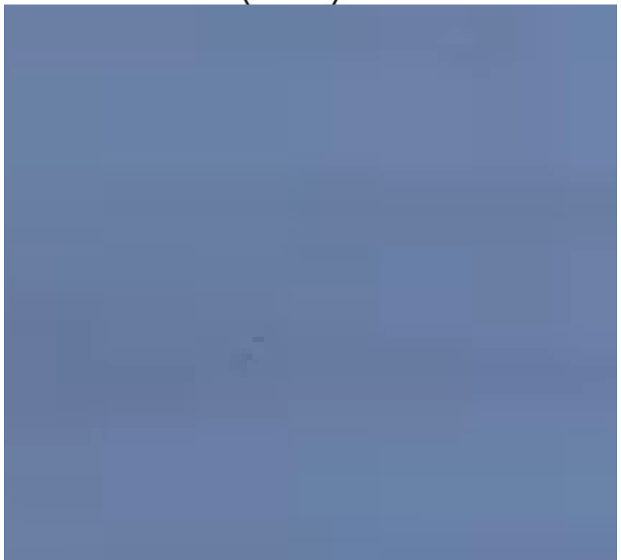
At each step:

1. Input view to a single layer network
2. Update network weights to increase familiarity of views (via Infomax learning rule)
3. Discard view (so memory doesn't scale with training route length



To return, visually scan the world

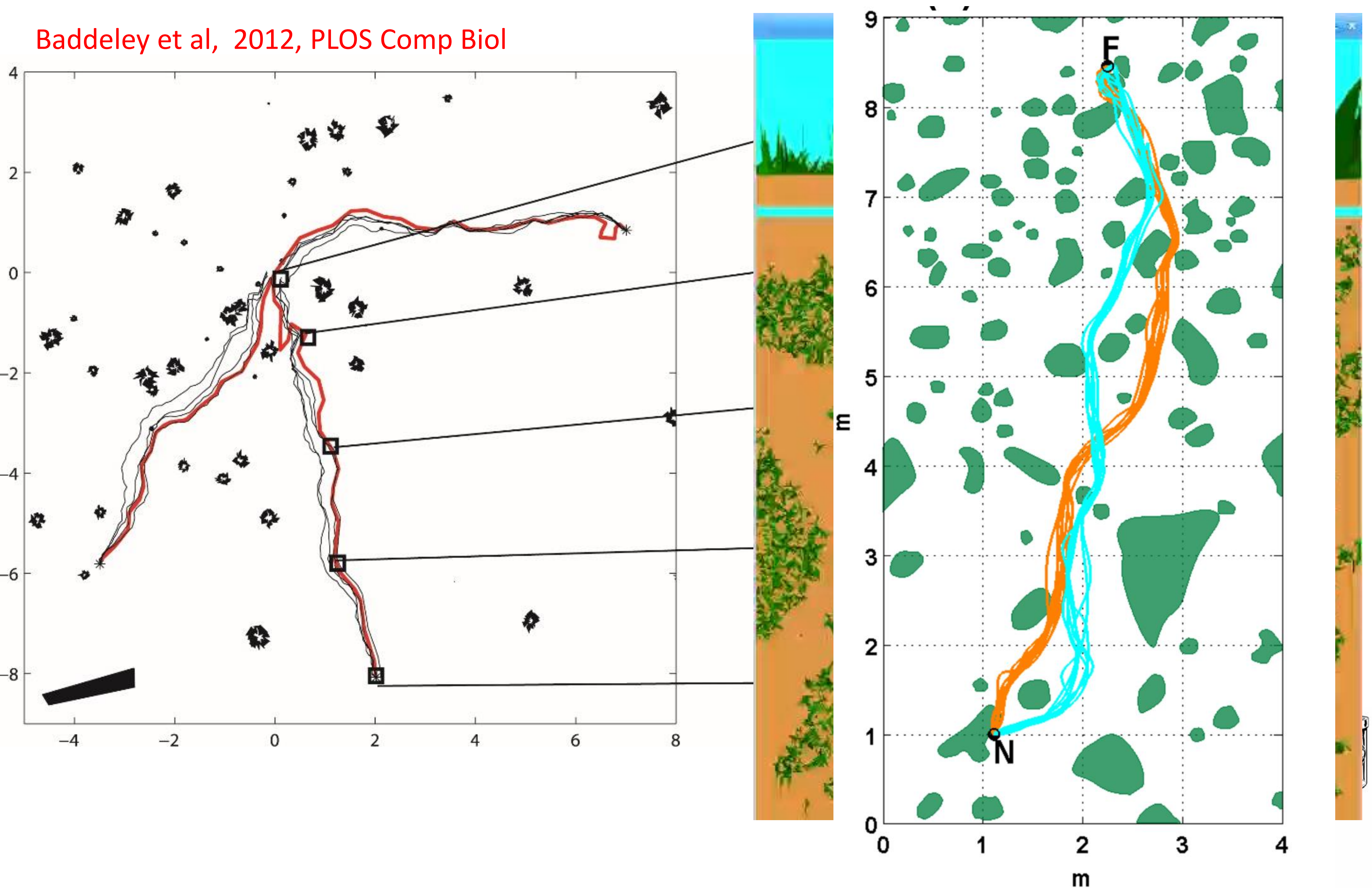
1. Input to ANN, get familiarity
2. Move in most familiar direction

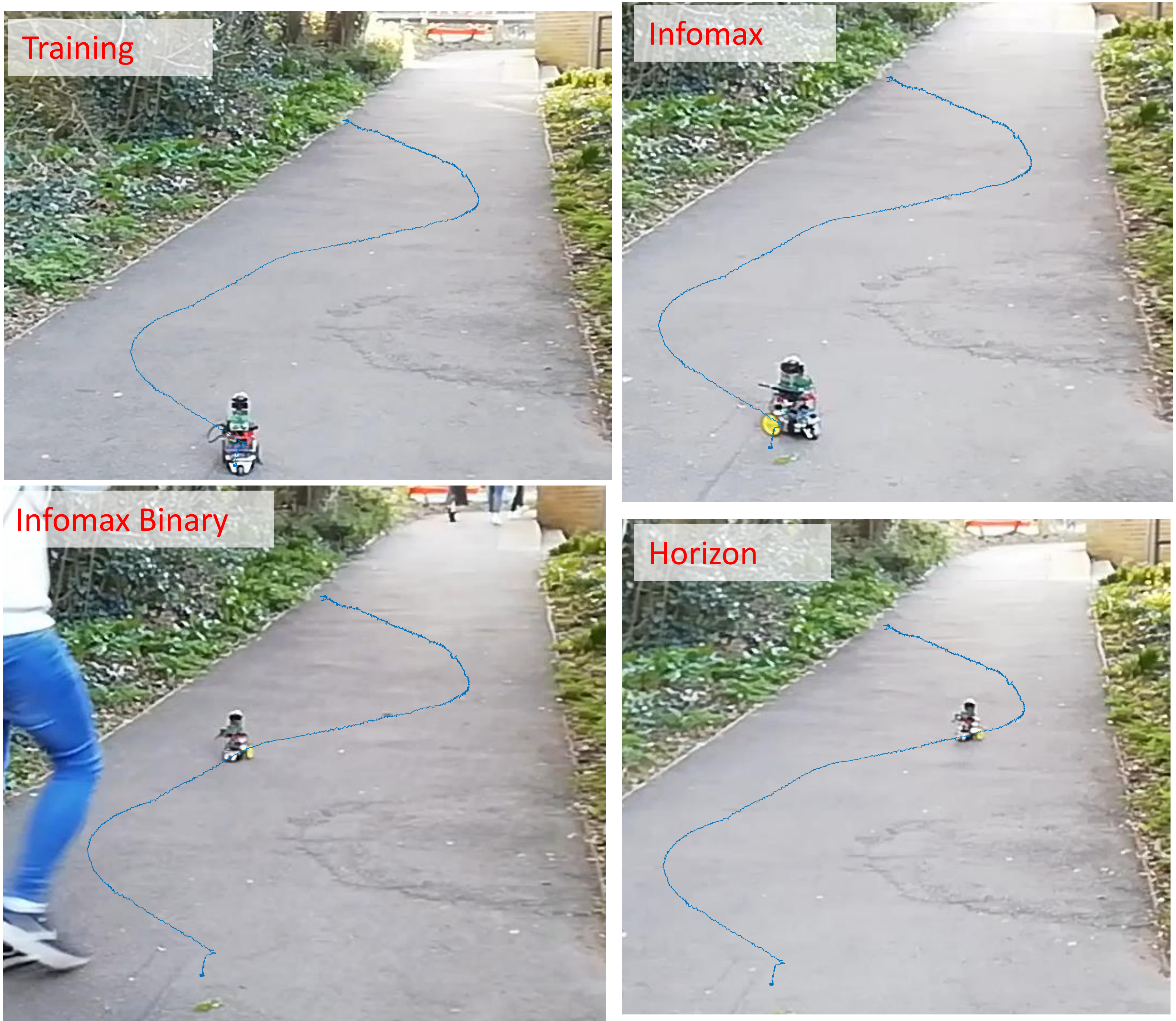


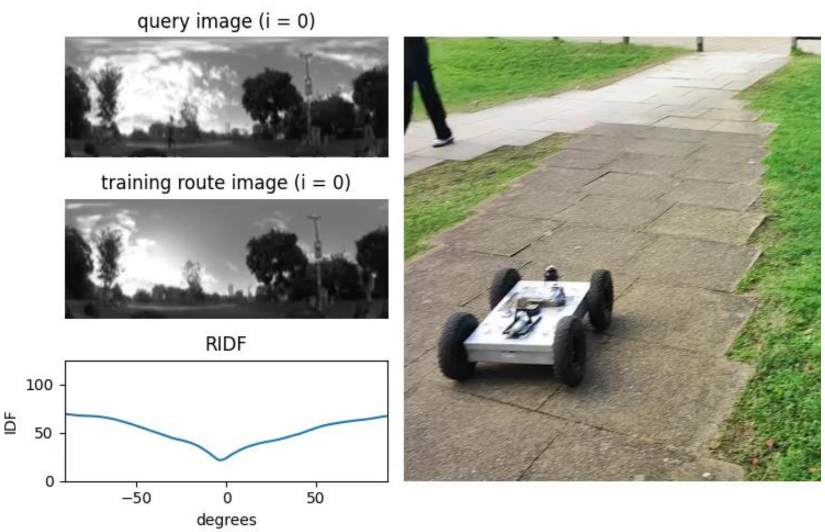
Baddeley et al, 2012, PLOS Comp Biol

Robust routes similar to ants

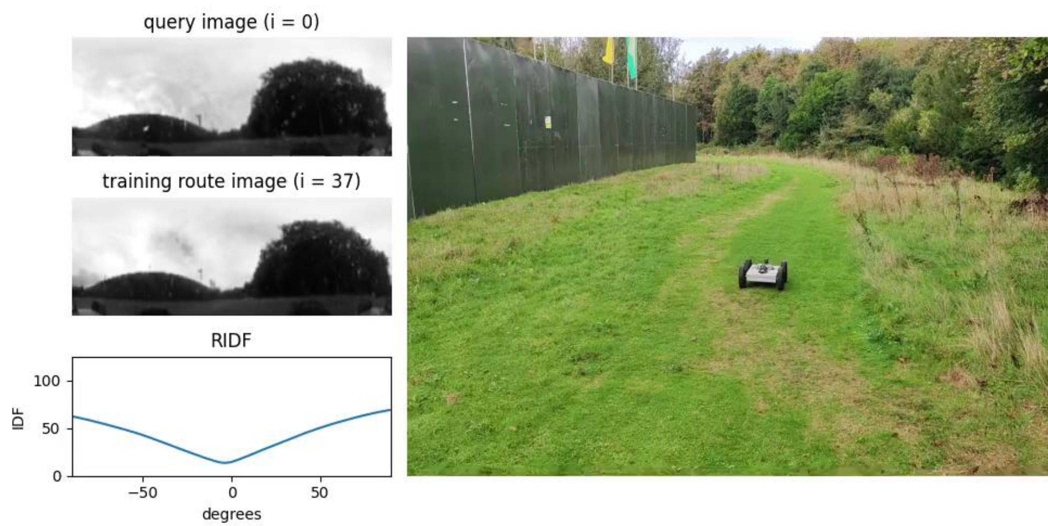
Baddeley et al, 2012, PLOS Comp Biol




Training
Infomax
Infomax Binary
Horizon



query image (i = 0)
training route image (i = 0)
RIDF
IDF
100
50
0
−50
0
50
degrees



query image (i = 0)
training route image (i = 37)
RIDF
IDF
100
50
0
−50
0
50
degrees

Insect Visual Navigation - Summary

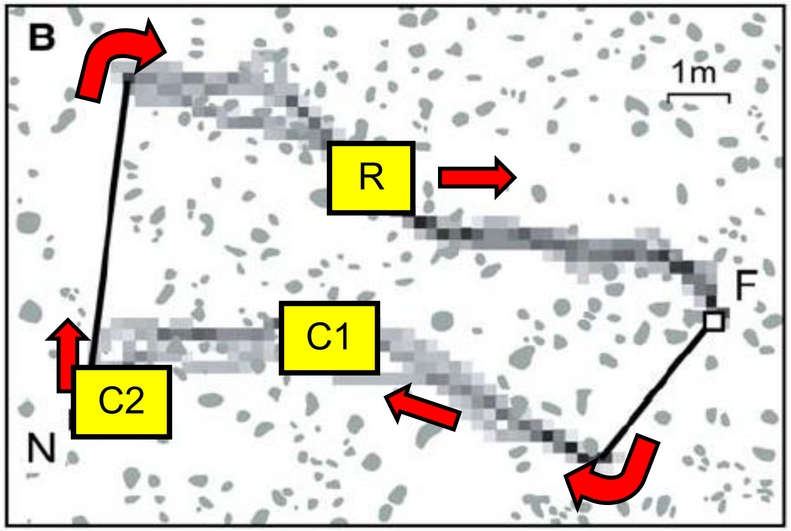
- Insect never needs to know where it is: not a mapping approach
- Not “where am I?” but “what do I do to get home?”
- Not “what is that object?” but “what does the world look like?”
- A toolkit of *procedural heuristics*: follow a route with simple action-based tricks

- It works because it’s built on and scaffolded by evolved behaviours … …
  – Path Integration
  – Visual scanning
  – Systematic search
- … which interact with learnt visual information (visual snapshots)
- Simplifies learning and makes process more robust

MINI BREAK

What are the limits of insect navigation?

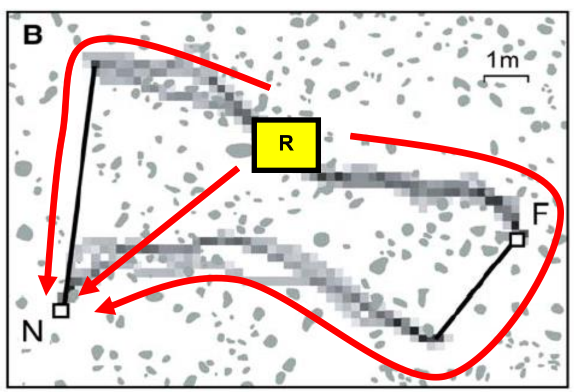
Insects insulate not integrate



Ants trained with spatially separate outbound and inbound routes.

Inbound ants displaced from C1 or C2 to R.

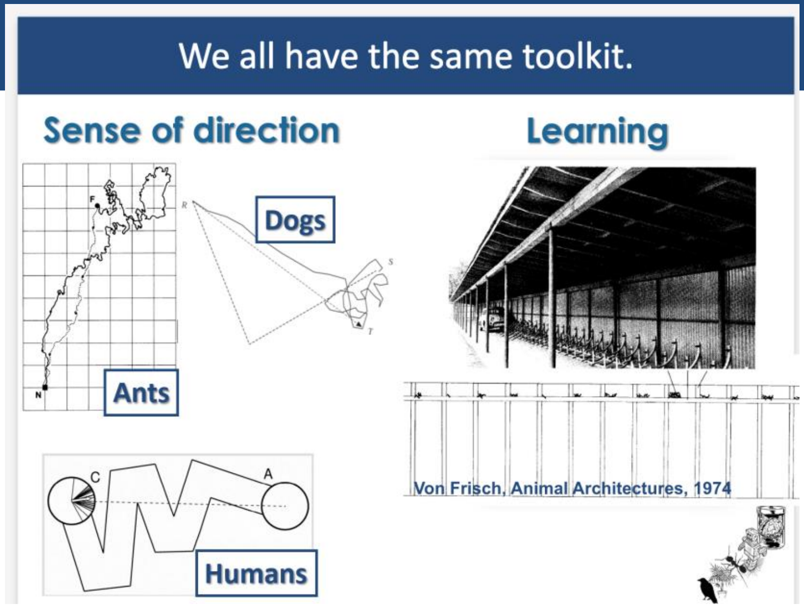
They could demonstrate their world knowledge with these routes:

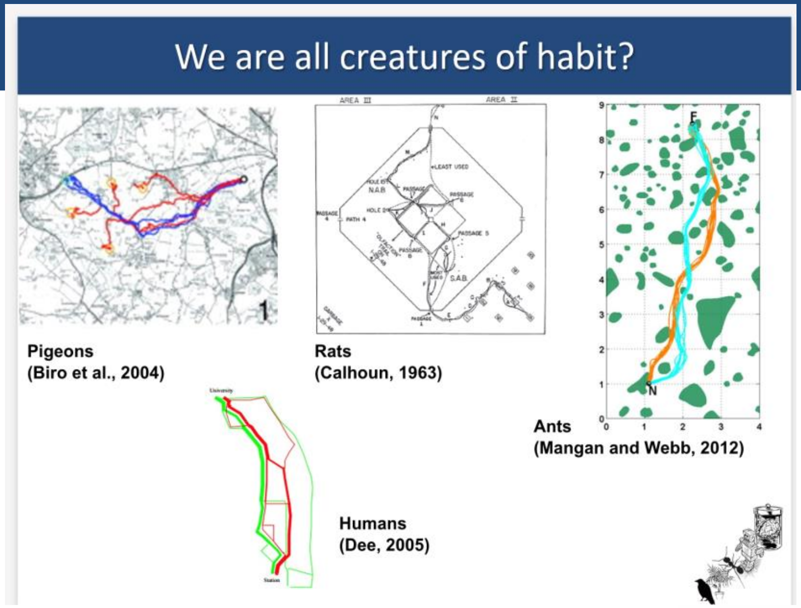


But in fact they are lost.

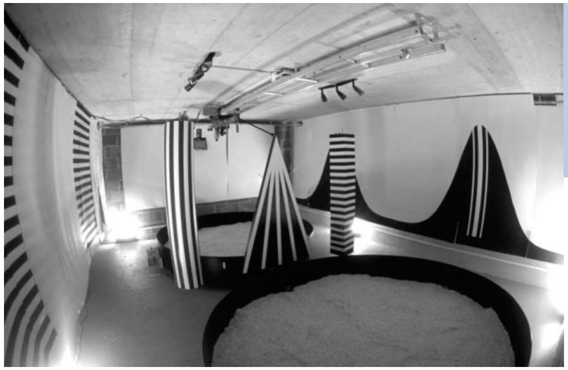
Wehner et al (2006)

What about bigger brained navigators?



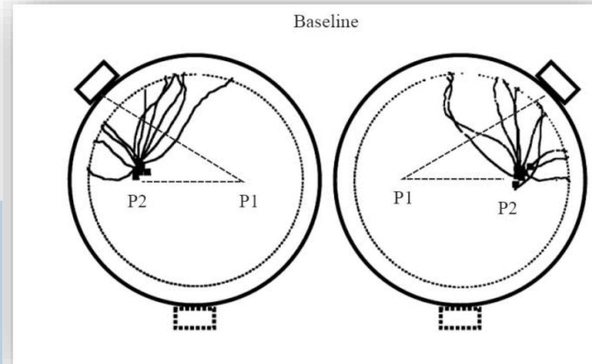


Cognitive maps in vertebrates: Combining modalities

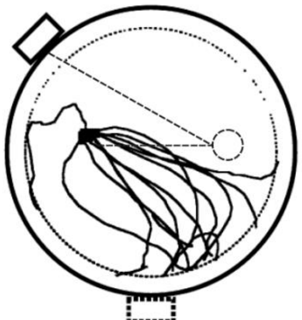


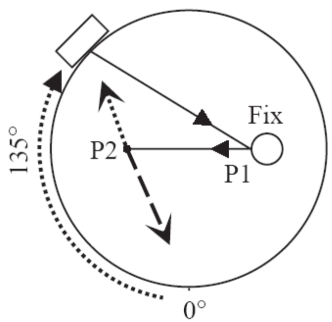
Phase 1 - Hamsters become familiar with a visually rich environment

Etienne et al (2004)



Test 1 – Arena rotated 135deg. In the dark, hamsters use Path Integration.





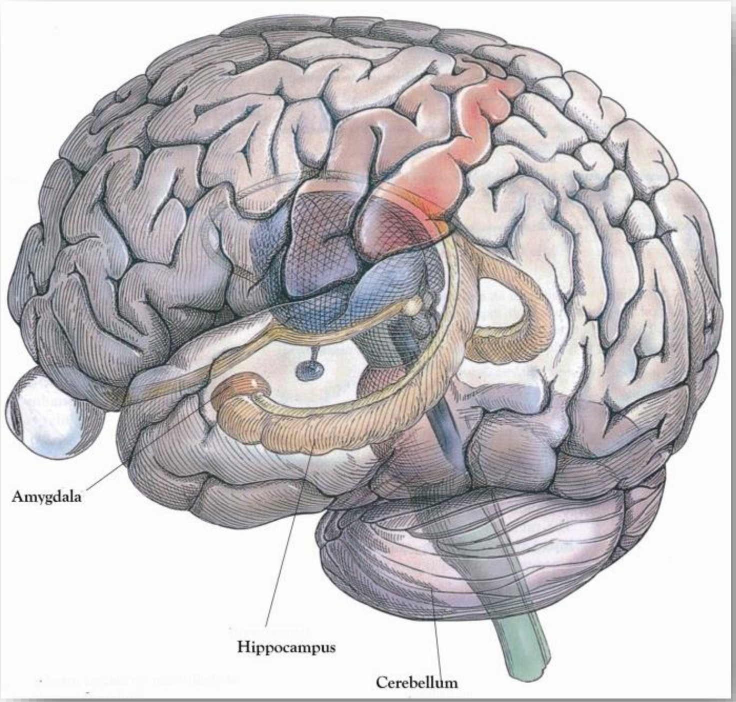
Test 2 – Hamsters given a short visual fix.

Hamsters were able to re-set their PI co-ordinates.

Visual and idiothetic information is combined.

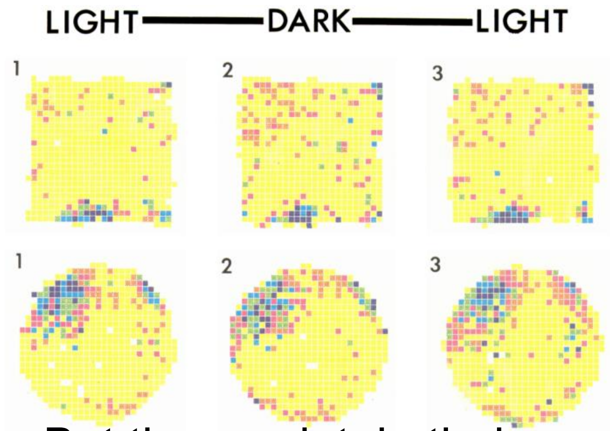
Hippocampus as site of spatial knowledge?

- Lesions of the hippocampus cause deficits in spatial behaviour.
- Taxi drivers who have performed "the knowledge" have a larger posterior hippocampus.



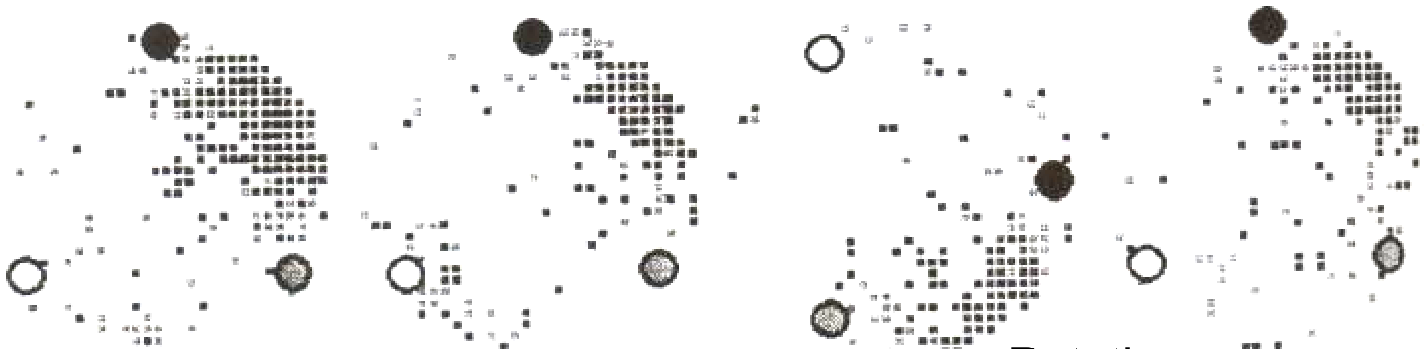
Place cells in the hippocampus

Firing is specific to location, independently of orientation.



But they maintain their firing in the dark

Place cells are tied to visual landmarks

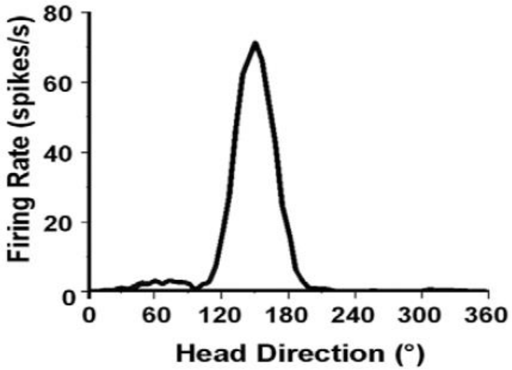


Rotation

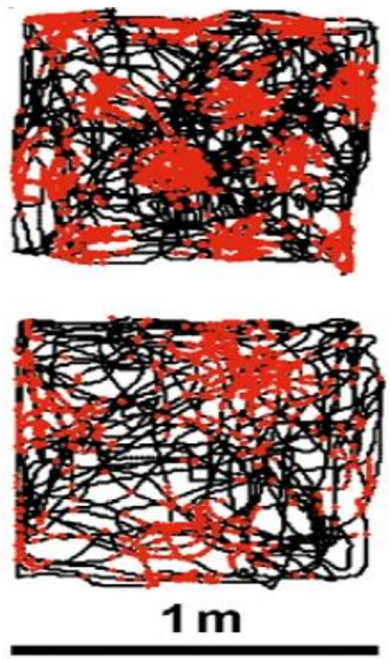
So place cells might be the site where visual and idiothetic information is combined.

Inputs to place cells

- Head direction cells
  - Direction independently of location
  - Population coding

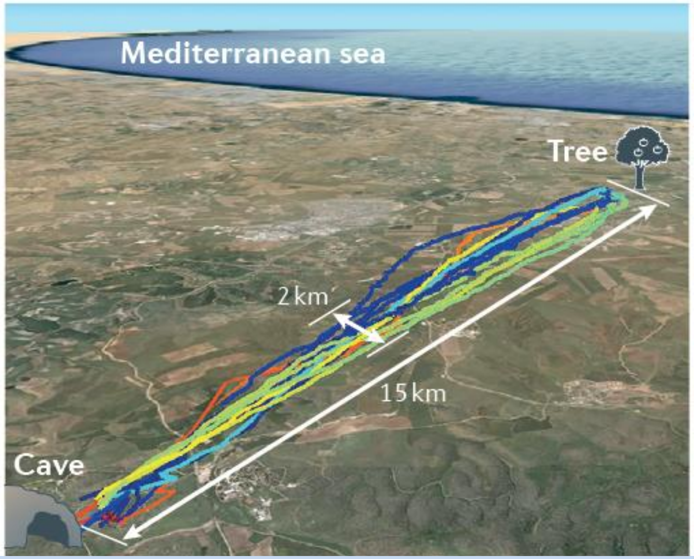


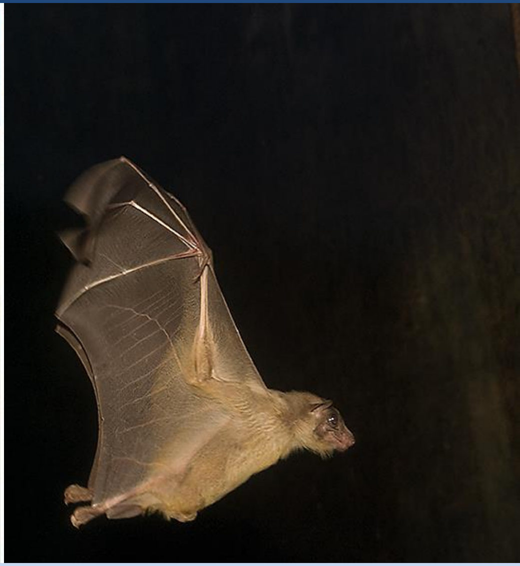
- Grid cells
  - Hexagonal array of firing fields.
  - Cells in different layers have different scales but the same orientation.



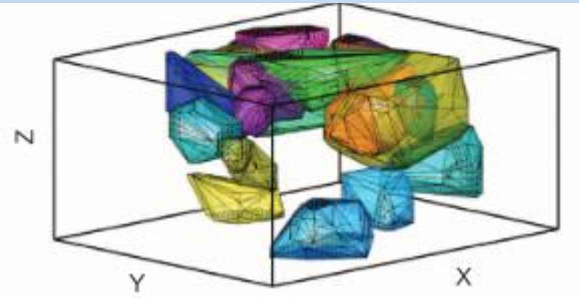
Situatedness and navigational mechanisms

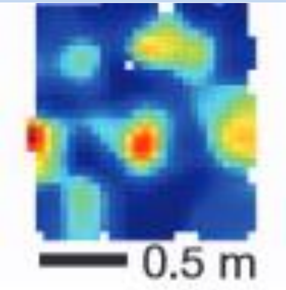
Egyptian fruit bats

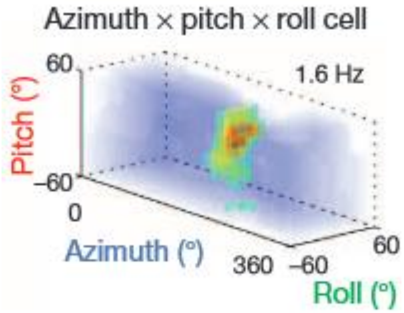




At the tree scale resemble rats, what about the route scale?







Place cells **Grid cells** **HD cells**

Geva-Sagiv et al., 2015

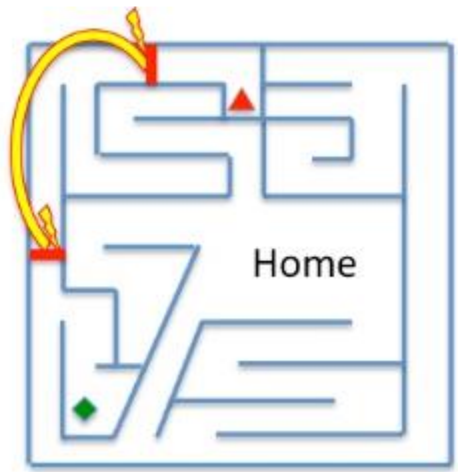
Interim summary

- Insects don’t combine learnt visual information with idiothetically generated information.

- Behaviour and neurophysiology suggest that vertebrates do.

- Do place cells give vertebrates a cognitive map?
  - The ‘cognitive map’ metaphor is ‘top-down’ and anthropomorphic.
  - It doesn’t address the behavioural output.

Map-like knowledge doesn’t come easily



Logical Maze

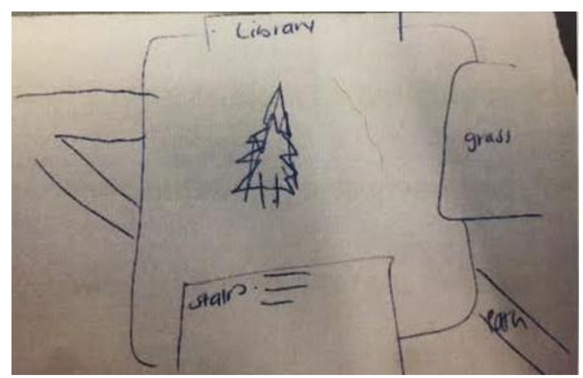
Wormhole condition

Subjects are not impaired navigating in impossible mazes that cannot be mapped

Schnapp and Warren 2007
Glennerster 2016

Subjects who haven’t used a map of a place are poor at producing a map

Graham et al (pilot)

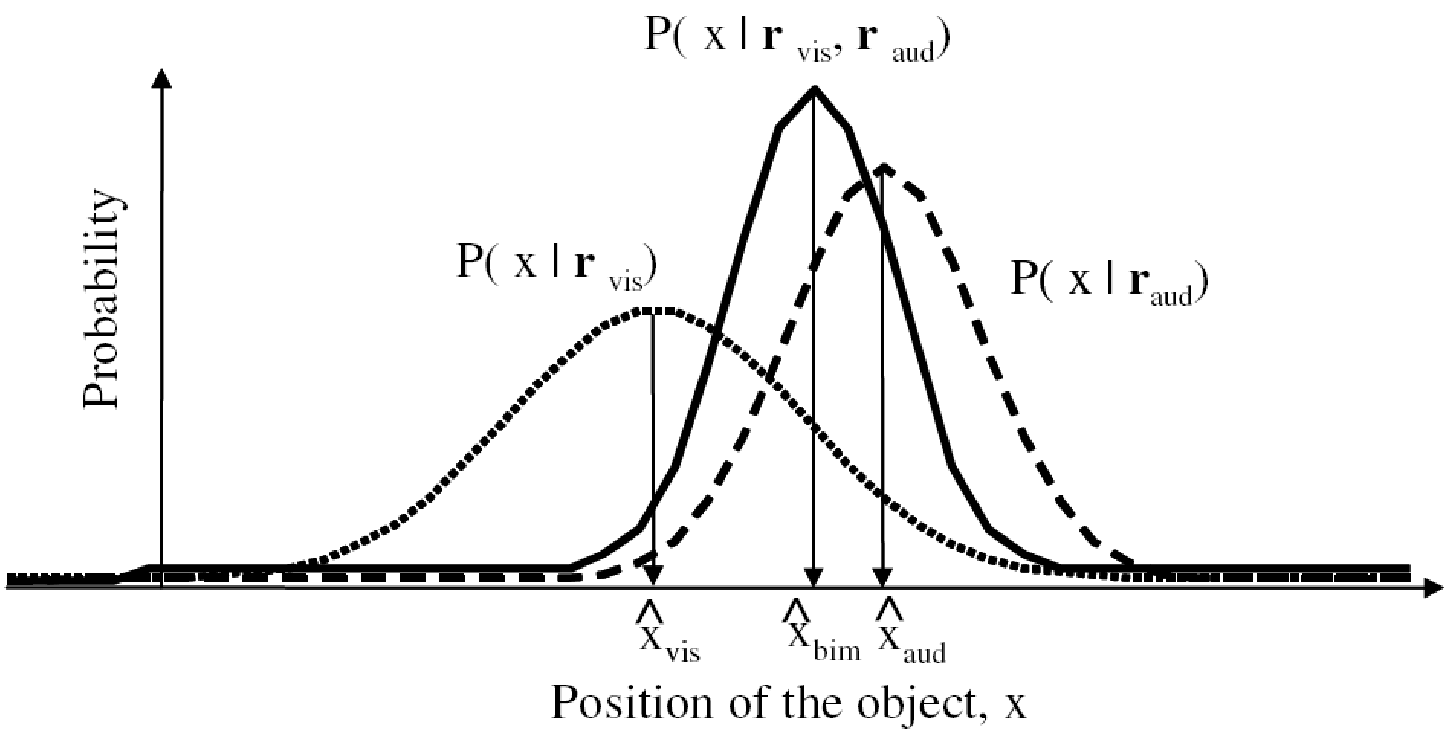


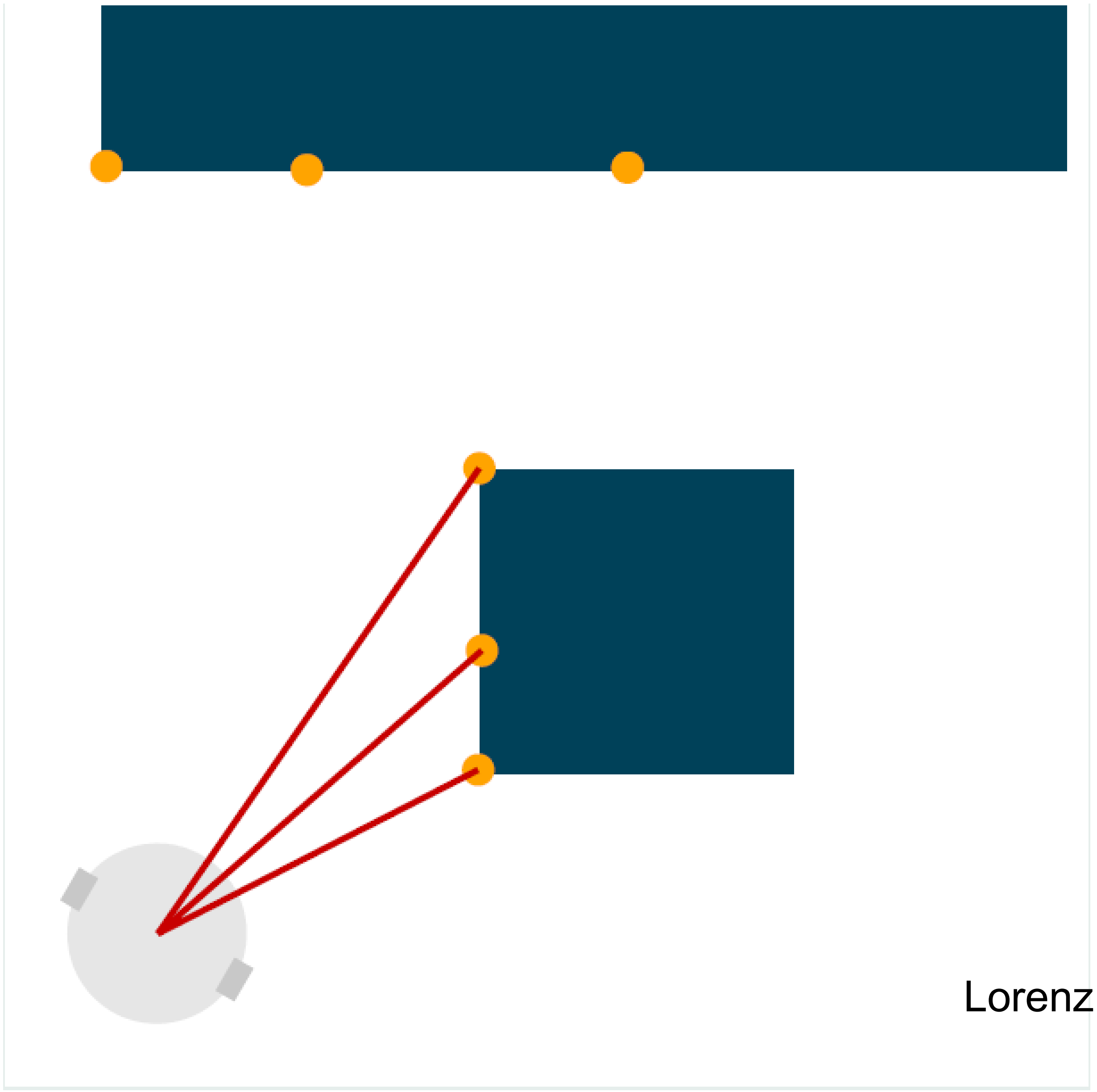
And these maps don’t improve from 1st to 2nd to 3rd years

How do cutting edge robot navigation algorithms combine sensory inputs?

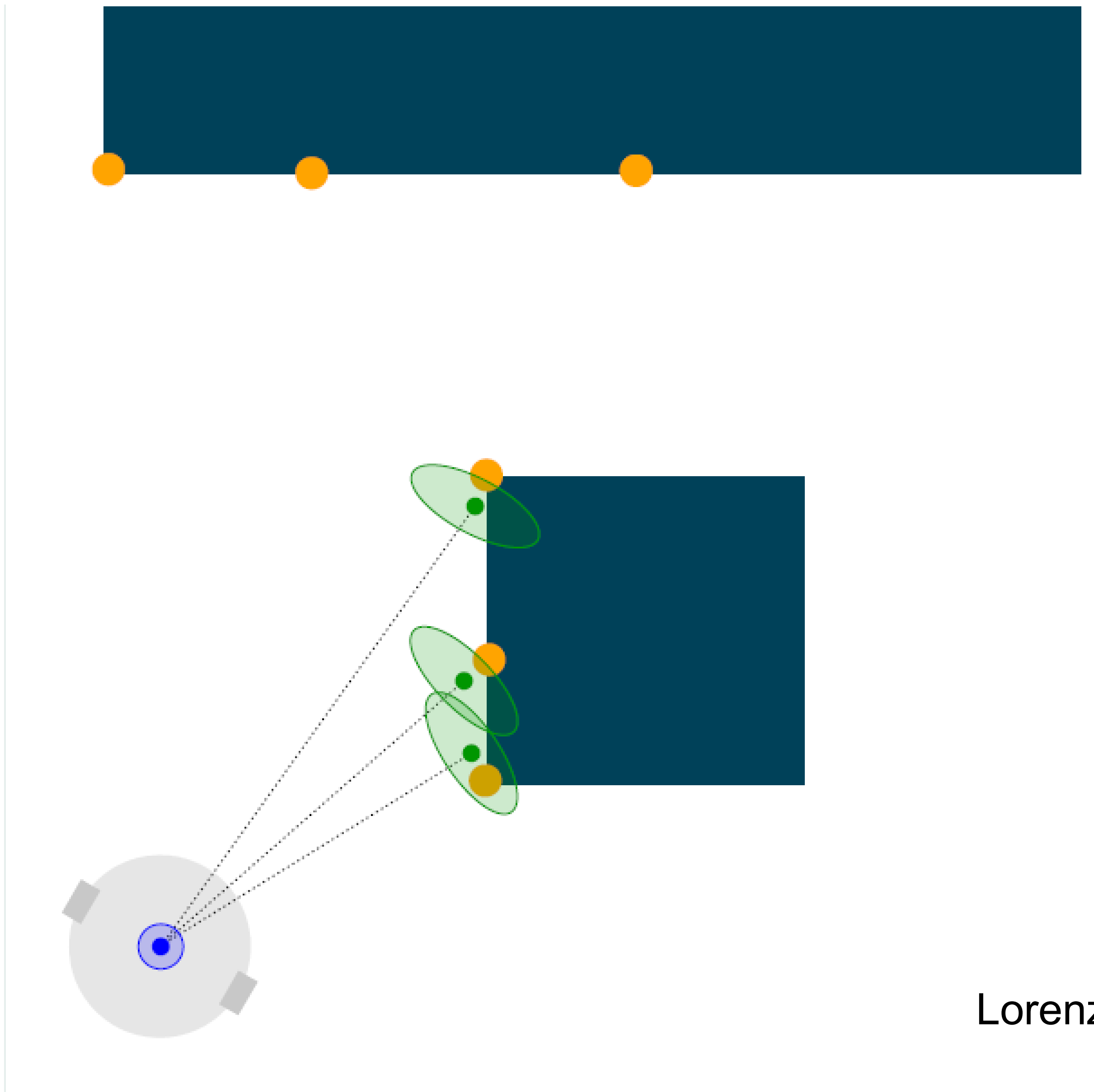
Robotic SLAM

- Simultaneous Localisation and Mapping (SLAM)
- Sense positions of features in the world;
- Move, sense positions again, and update position estimate by how features should have moved (based on estimate of own movement)
- Estimates take account of how uncertain signals are (uncertainty = variance = spread of distribution of estimates)



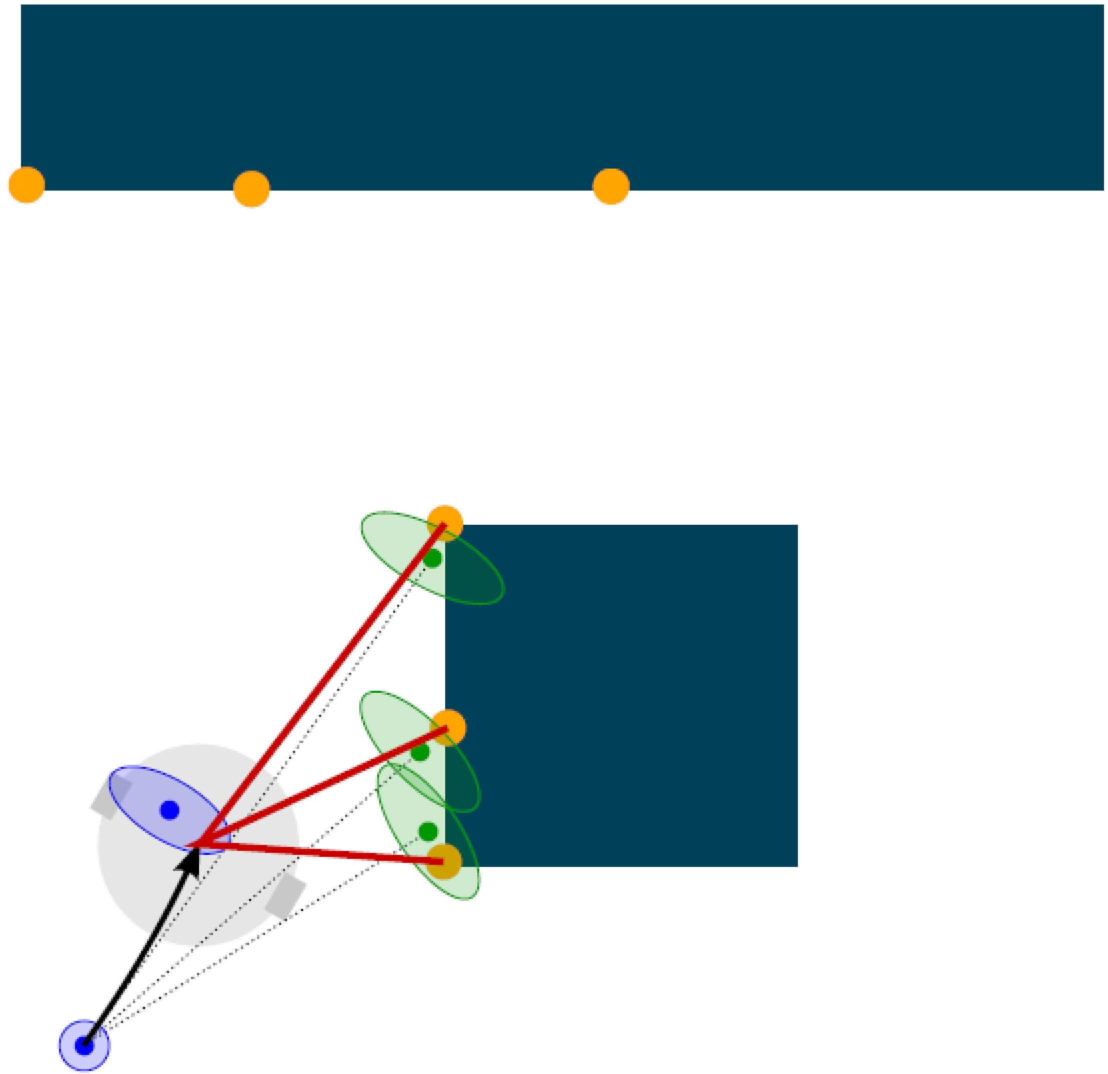


Lorenz Gerstmayr

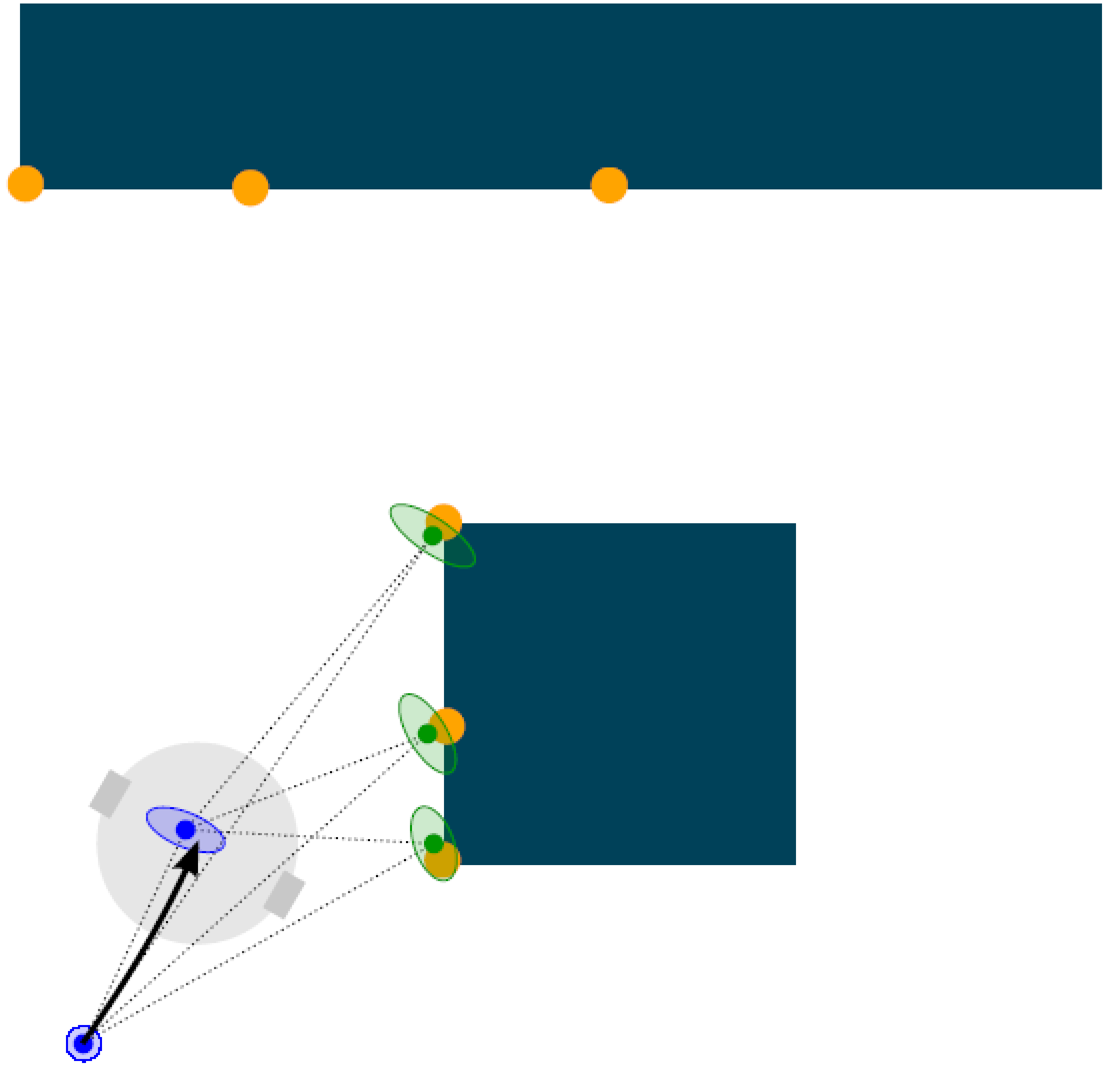


Lorenz Gerstmayr

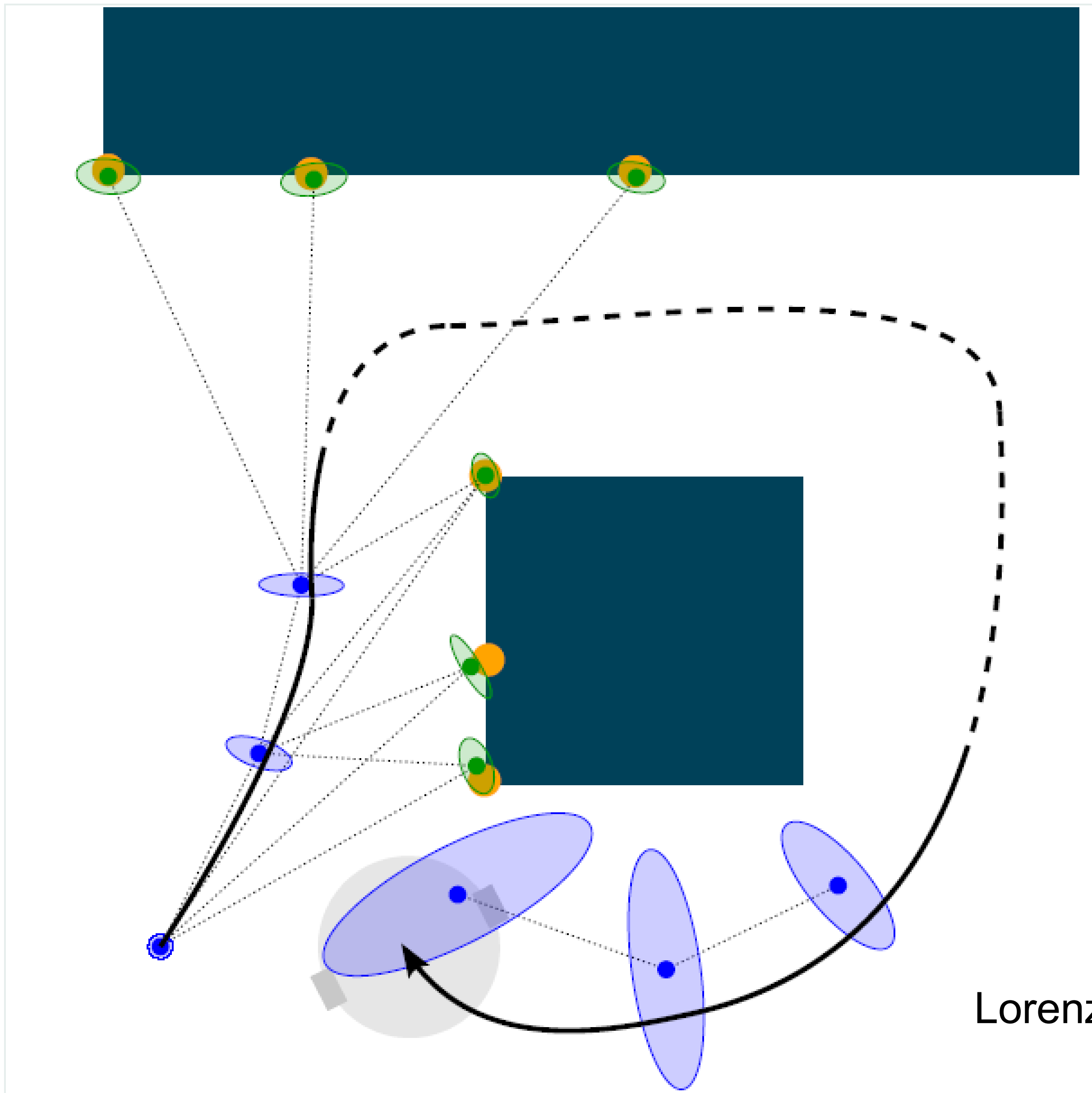
[Green ellipses illustrate 2d uncertainty]



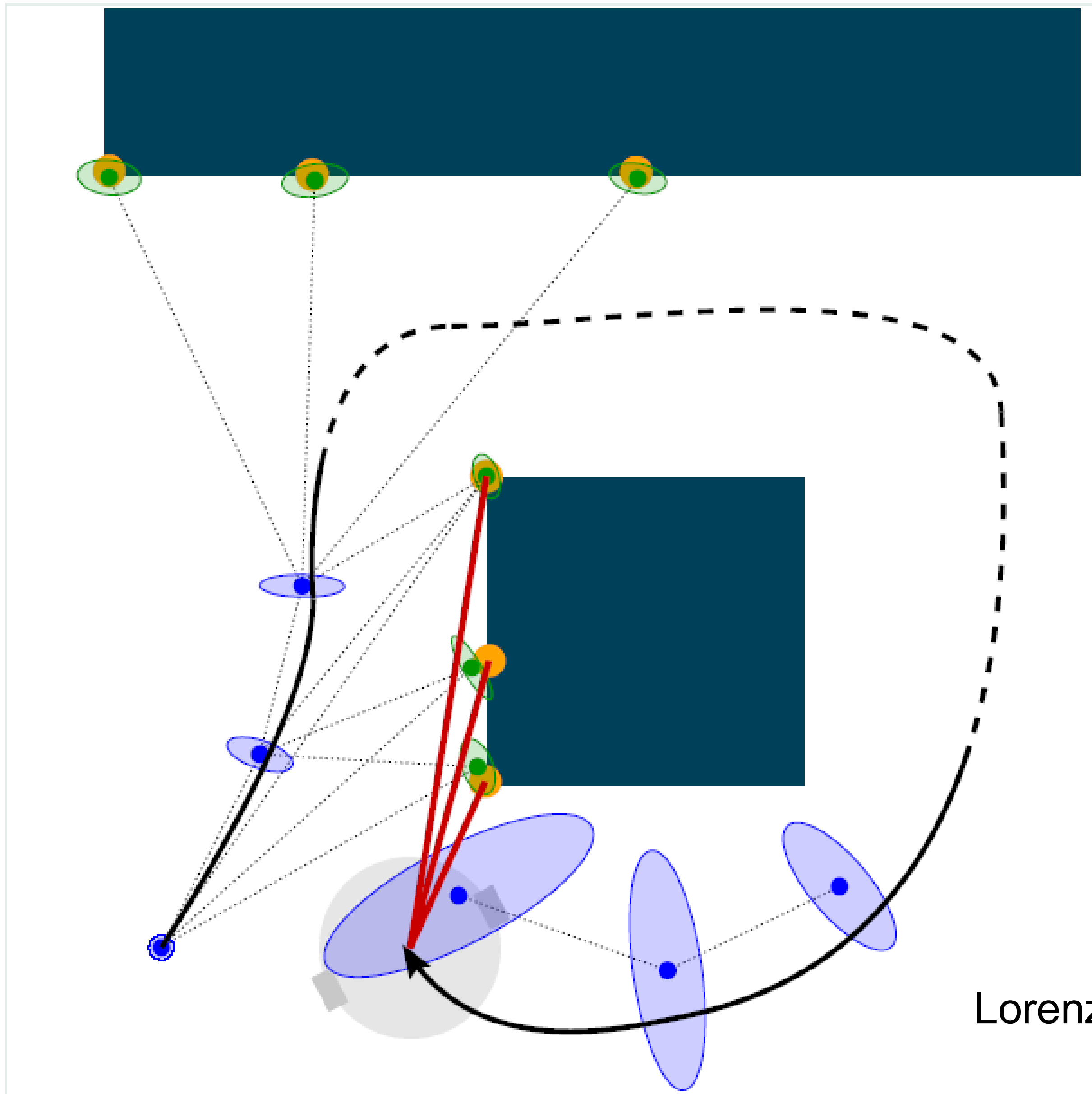
Lorenz Gerstmayr



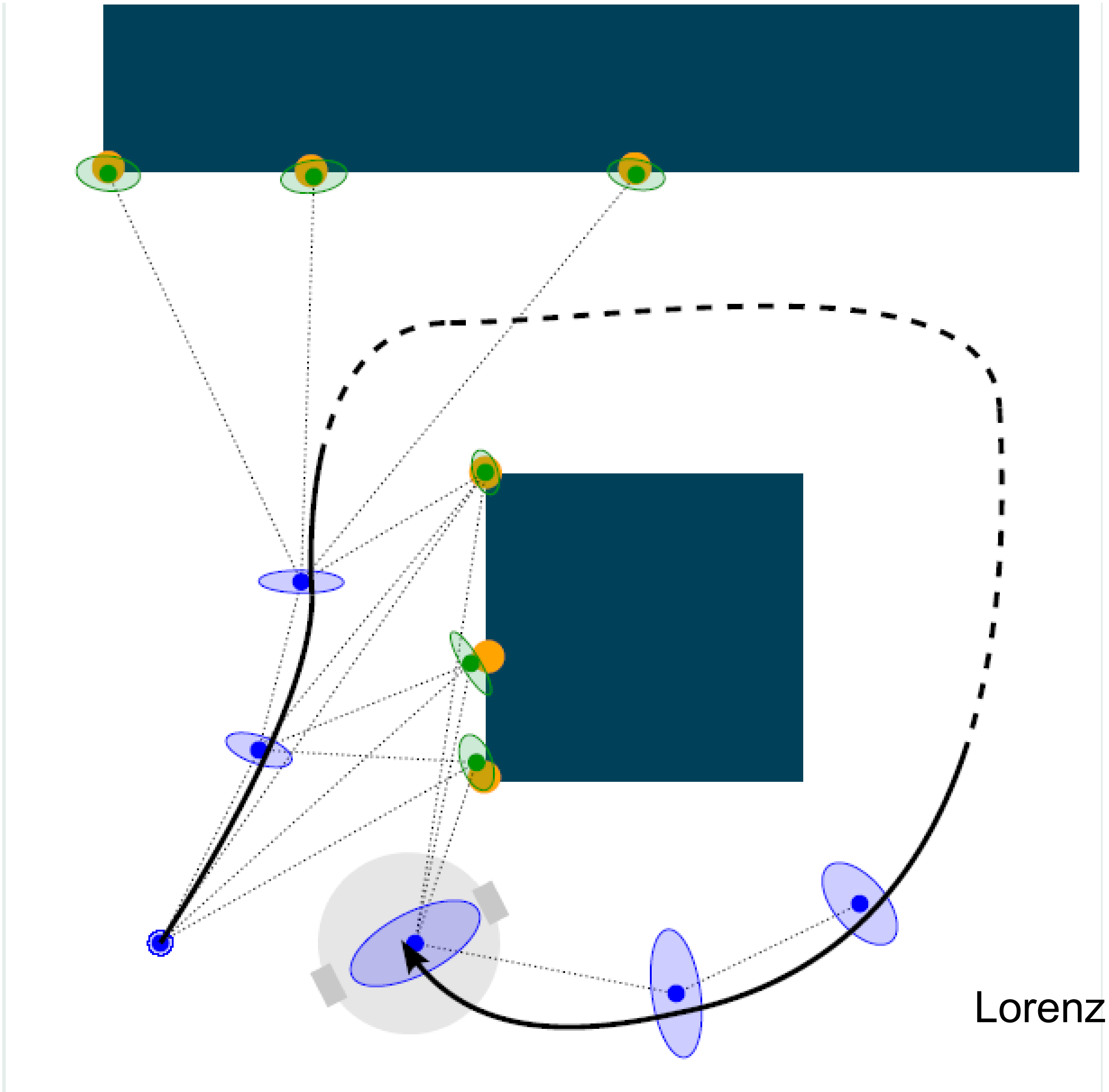
Lorenz Gerstmayr



Lorenz Gerstmayr



Lorenz Gerstmayr



Lorenz Gerstmayr

final step is "loop closure": back to known place so corrects drift

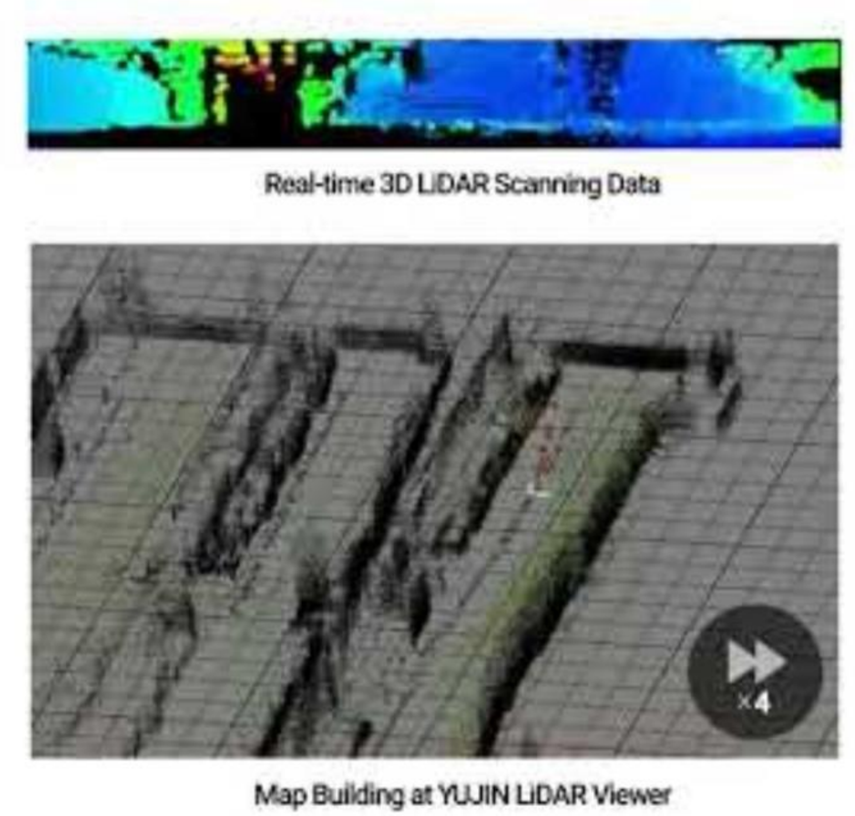
Monocular SLAM in action – Andrew Davison

https://www.youtube.com/watch?v=UVb3AFgabu8&ab_channel=ArghyaChatterjee

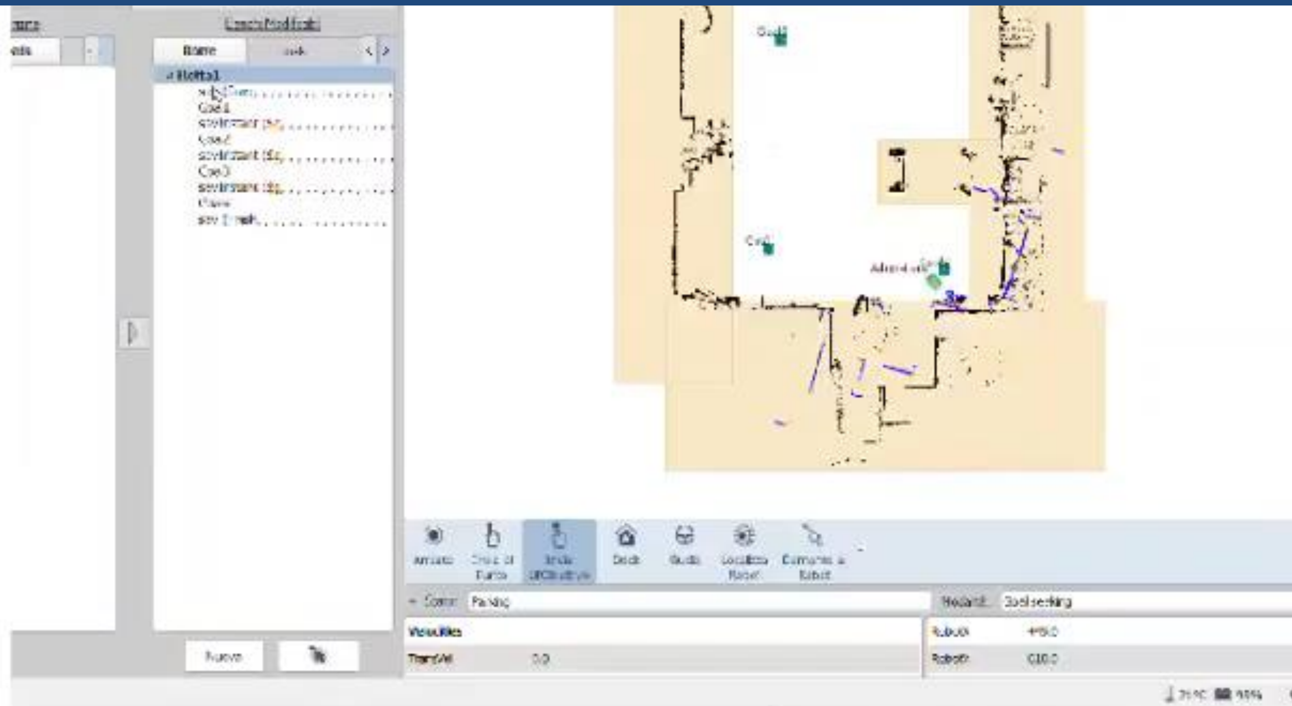
- Many SLAM variants: Here single camera but depth is important so used stereo, then RGBD and now scanning laser range finders (LIDAR) and GPS
- Simple maths but lots of computation, especially matching points between frames and loop closure but this is helped by faster sampling
- Better self-movement from improved IMUs helps as well

LIDAR SLAM

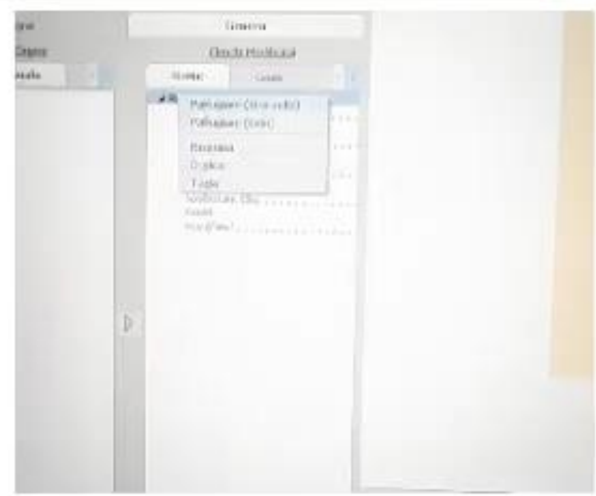
- This video shows a map being built and refined by **LOTS** of sampling: https://www.youtube.com/watch?v=r4BqdNuty2s



Odometric SLAM in action: Omron cleaning robot



- Inertial/Odometric SLAM: localisation over mapping
- Given map, track position very accurately
- Improved IMUs give more accurate instantaneous self-movement estimate (especially for drones)
- Improve accuracy by estimating instantaneous movements from feature movements in consecutive frames (rather than estimating position accurately)



Or focus on Mapping with accurate GPS localisation

- https://www.youtube.com/watch?v=YQDKb3mhSmU
- LIDAR combined with cameras and RTK GPS [from 40 secs]

Robot Navigation - Summary

- SLAM provides a mathematical framework by which you can integrate remote sensing (vision or LIDAR) and idiothetic information.
- But it is computationally expensive and doesn’t address problem of visual feature extraction in complex natural worlds nor how to use the map
- Doesn't appear to be how animals navigate: learning routes is much more efficient!
- Odometric SLAM shows how sensor and computational developments can allow "simple" algorithms to succeed by estimating position from fast samples of visual motion (like flies!)

Today’s Reading

Recommended

- Graham (2010) Insect Navigation. *Elsevier Encyclopedia of Animal Behaviour.*
- Geva-Sagiv et al. (2015) Spatial cognition in bats and rats: from sensory acquisition to multiscale maps and navigation, *Nature Rev. Neurosci*
- Bennet (1996) Do animals have cognitive maps? *JEB*