ARC Centre for Complex Systems, Australia

www.accs.edu.au

Distributed Control in Network-based Systems: a complex systems approach

Prof Peter Lindsay

Boeing Professor of Systems Engineering, University of Queensland

Director, ARC Centre for Complex Systems (ACCS)

ARC CENTRE FOR COMPLEX SYSTEMS

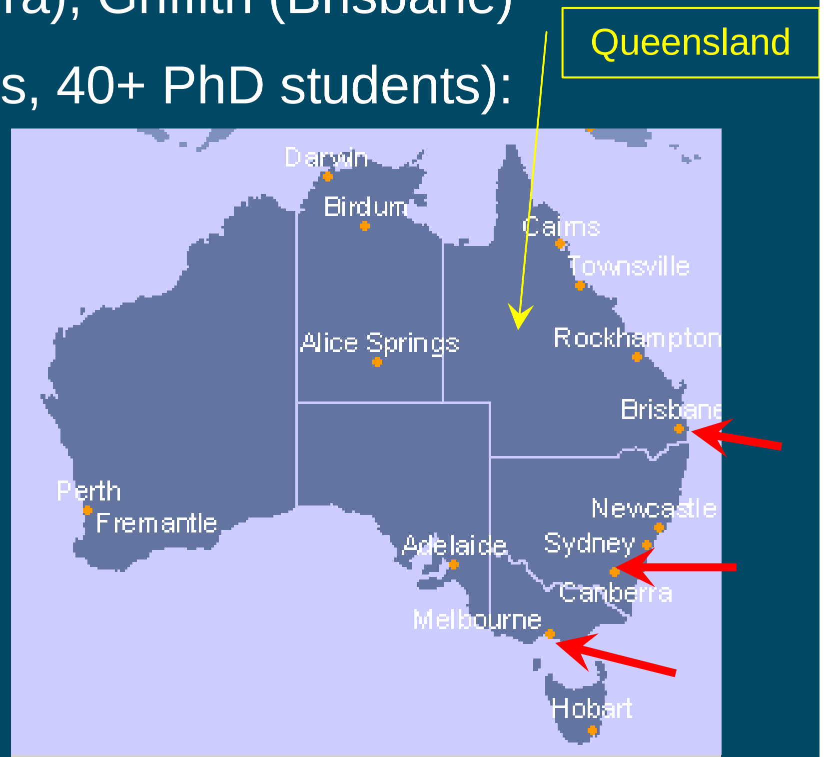
Outline of presentation

- About the ARC Centre for Complex Systems
  - Theme is theory & modelling of complex, adaptive network-based systems without central control
- 2 of our 3 main research programs:
  - Genetic Regulatory Networks
    - models of gene-based control of growth & structure in biology
  - Air Traffic Control (ATC):
    - modelling & simulation infrastructure for investigating new ATC operational concepts

ARC CENTRE FOR COMPLEX SYSTEMS

ACCS: size & participants

- $US1.2M pa for 2004-2007
  - primarily from the Australian Research Council (ARC)
  - for cross-disciplinary basic research
- Based at UQ (Brisbane) with nodes at Monash (Melbourne), Aust Defence Force Academy (Canberra), Griffith (Brisbane)
- Inter-disciplinary team (80+ researchers, 40+ PhD students):
  - systems & software engineering
  - *Complex Systems Science* theorists
  - computational science, visualisation
  - data mining, machine learning
  - human factors
  - economics
  - bioinformatics

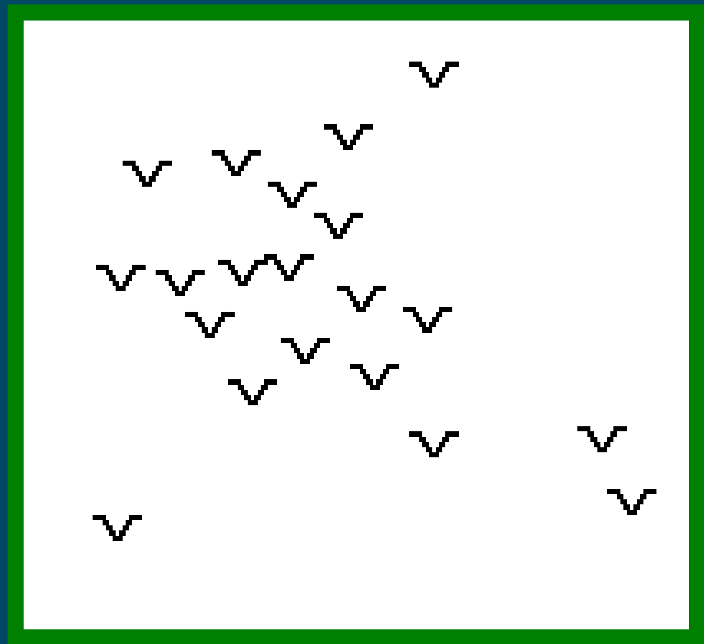


ARC CENTRE FOR COMPLEX SYSTEMS

Distributed control in network-based systems

Complex Systems Science

- Holistic view vs reductionism
  - "The whole is greater than the sum of the parts"
- Re-emerged in 1980's from the "soft sciences" (biology, sociology, economics)
  - now very active: e.g. Santa Fe Institute, New England CSI
- One branch seeks to understand how simple rules about interactions between components can generate complex behaviour
  - e.g. Flocking behaviour from 3 simple rules

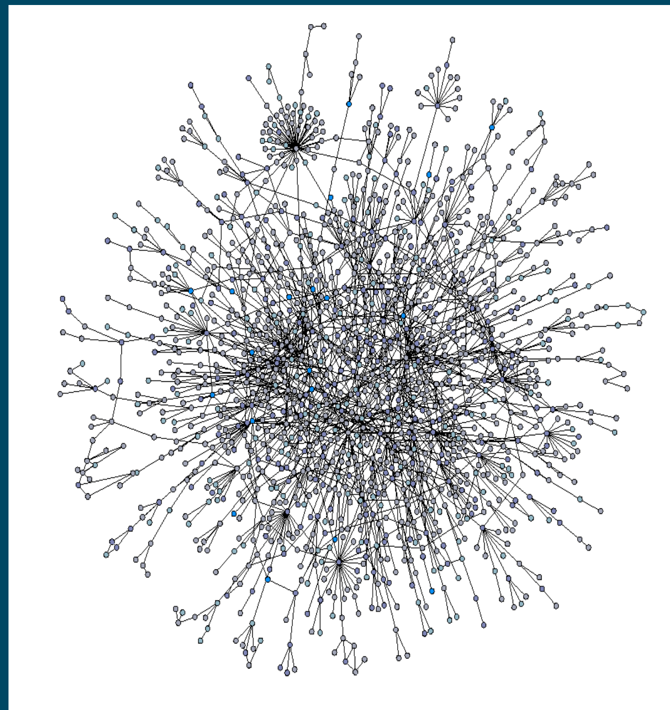


ARC CENTRE FOR COMPLEX SYSTEMS

Complex Systems Science (2)

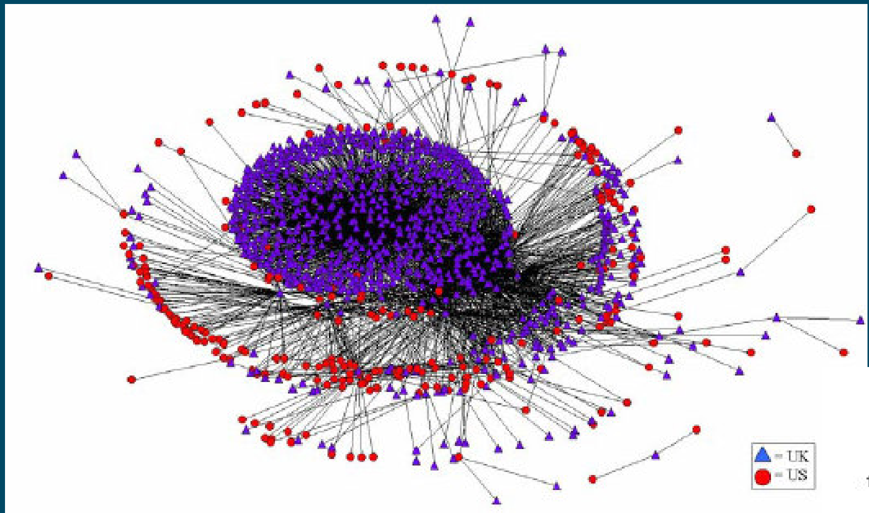
Another branch studies networks and how their topology affects system properties: eg

- scale-free networks: function Nodes(k) = “# nodes with k neighbours” follows an inverse power law
  - typically $k^{-2.3}$
  - – Internet backbone, metabolic reaction, telephone calls, www, airline routes

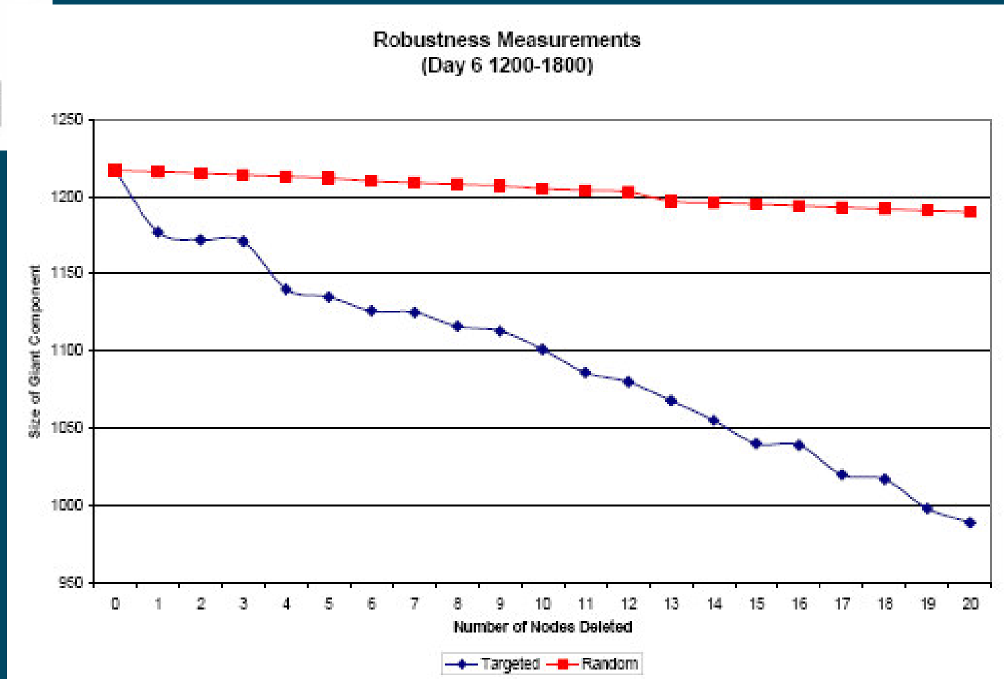


ARC CENTRE FOR COMPLEX SYSTEMS

Network degradation



From D Jarvis, *A methodology for analyzing complex military Command And Control (C2) networks*



- highly resistant to local failures
- highly vulnerable to attacks on hubs

The Centre's research program

- Focus on theory and modelling of complex, adaptive network-based systems without centralised control
  - Investigate how complex system behaviours arise from simple agent behaviours & connections between agents
- Aim is to deliver theory, methods and tools for studying such systems

3 main application areas

- Genetic regulatory networks: how DNA controls growth & development of biological organisms
- “Free flight” air-traffic control: how to let airlines choose aircraft trajectories
- Evolutionary economic systems: how agents acting in networks (typically markets) lead to macro-economic behaviour

Plus “infrastructure” projects:

- eg Dependability of Computer-based Systems
  - Modelling system requirements for complex systems

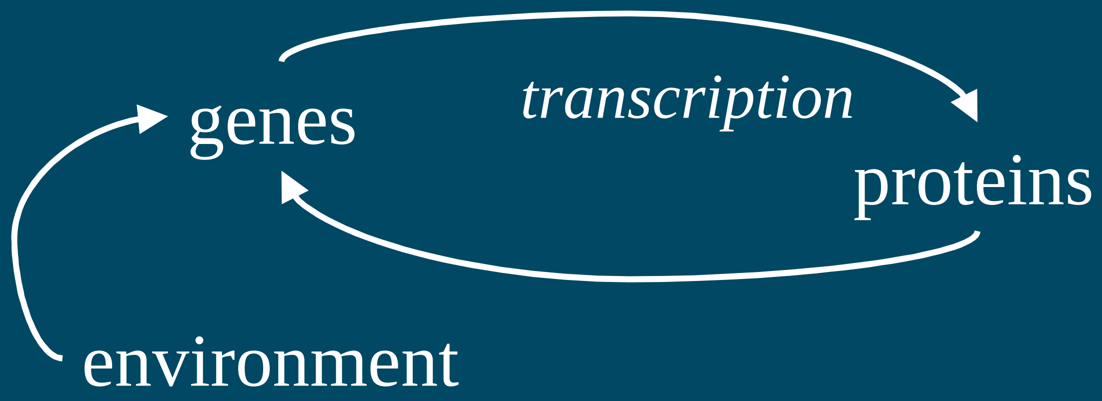
Outline of talk

- About the ARC Centre for Complex Systems
  - Theme is theory & modelling of complex, adaptive network-based systems without central control

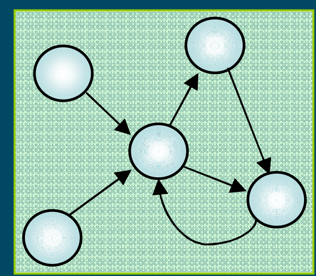
2 of the 3 main research programs:

- Genetic Regulatory Networks
  - models of gene-based control of growth & structure in biology
- Air Traffic Control
  - modelling & simulation of new ATC operational concepts

Gene regulation: a dummy's view

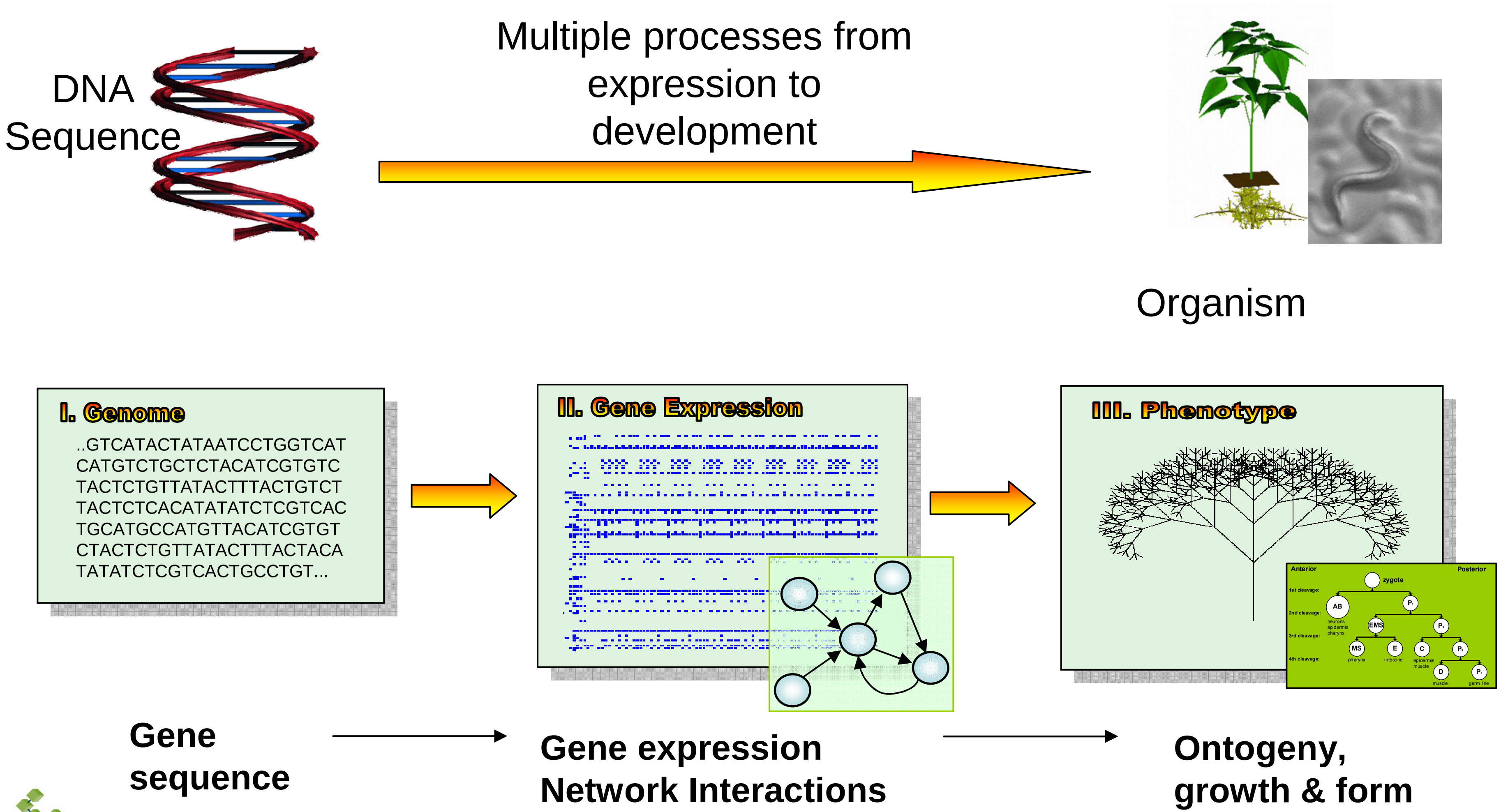


- As cells divide & DNA replicates, individual genes can get turned on ("get expressed") or off
- Gene expression state determines cell type
- There are networks of particular genes that regulate gene expression
  - ie, control which genes get turned on & turned off in the next generation of cells, when cells divide



- Biologists are developing insights into the different forms of control used in nature

Gene Regulatory Network Modelling



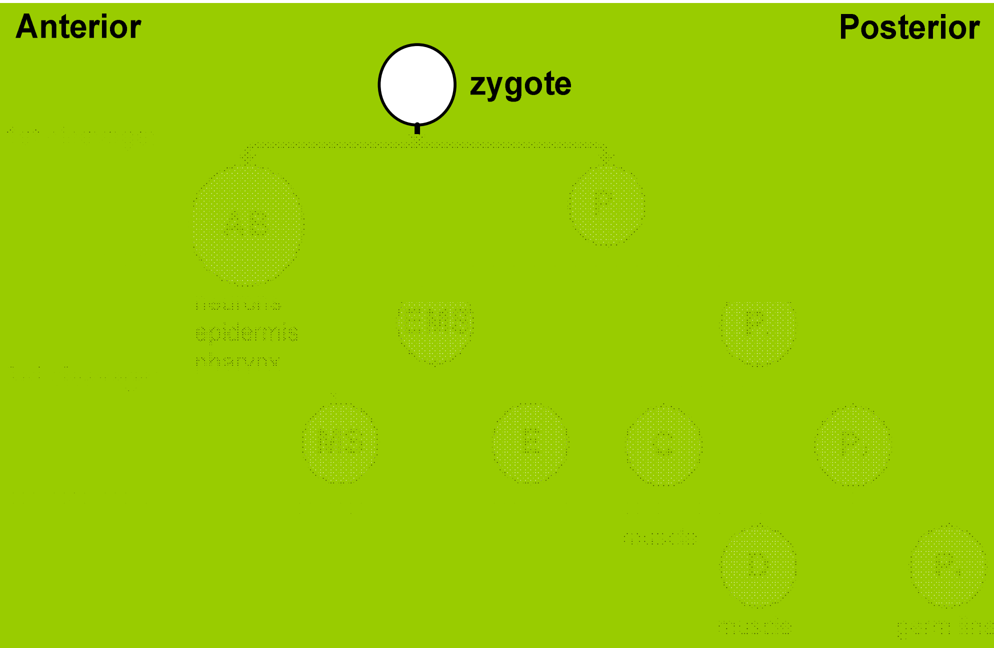
ARC CENTRE FOR COMPLEX SYSTEMS

Modelling of organism ontogeny

- Ontogeny = cell type lineage (type & position)
- *C.elegans* nematode worm
  - 10 “generations” of cell divisions up till birth (600 cells)
  - 959 cells in adult worm

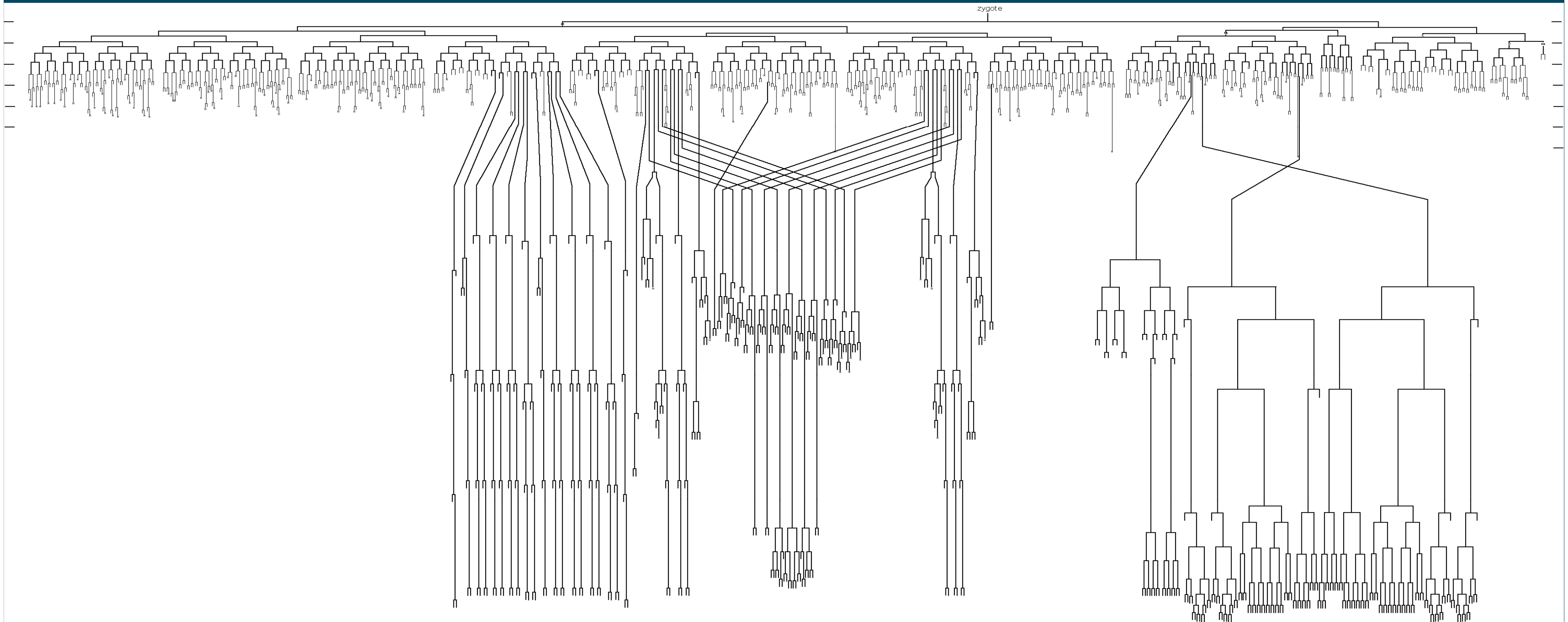
ARC CENTRE FOR COMPLEX SYSTEMS

C.elegans first 5 cell divisions



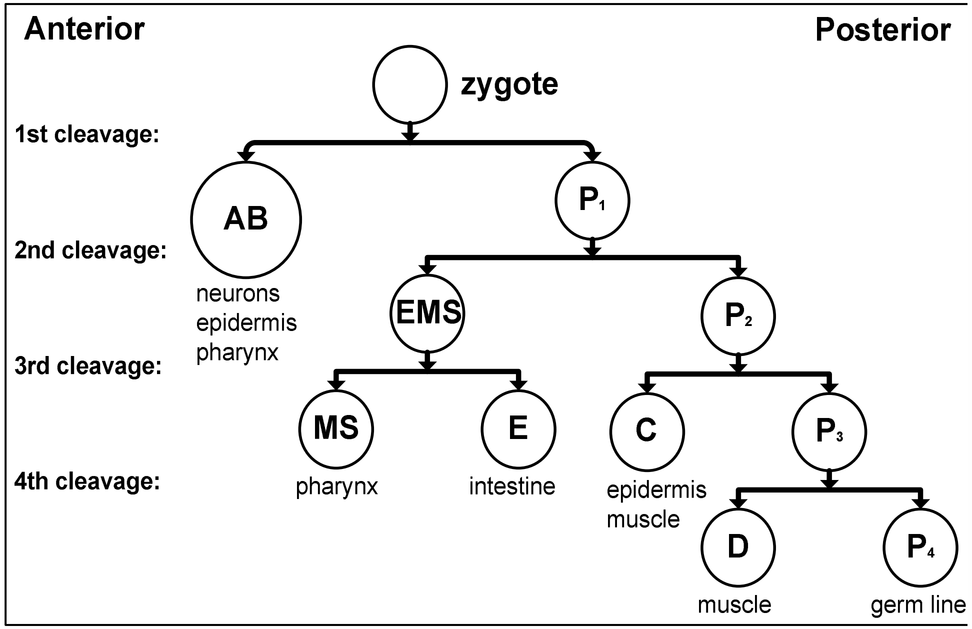
Images from celdev.mov

Cell lineage tree for *C. elegans*



Cell lineage model

Discovering a GRN by fitting to data

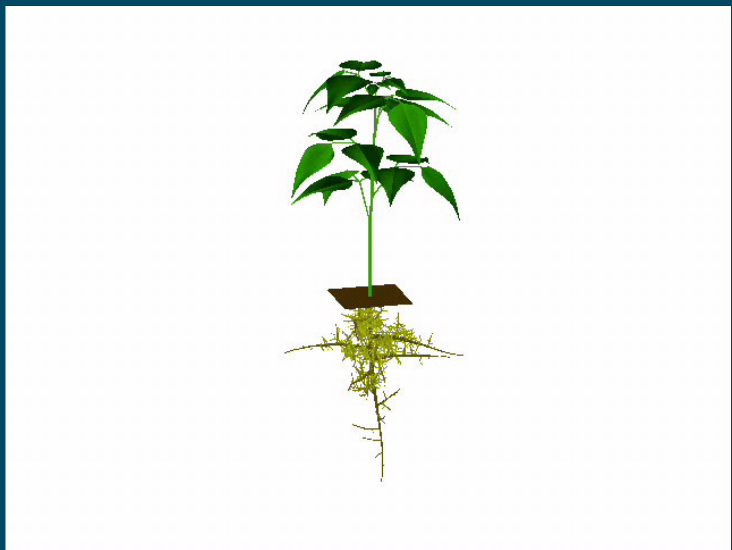


Simulations by Nic Geard

ARC CENTRE FOR
COMPLEX SYSTEMS

Models of plant growth

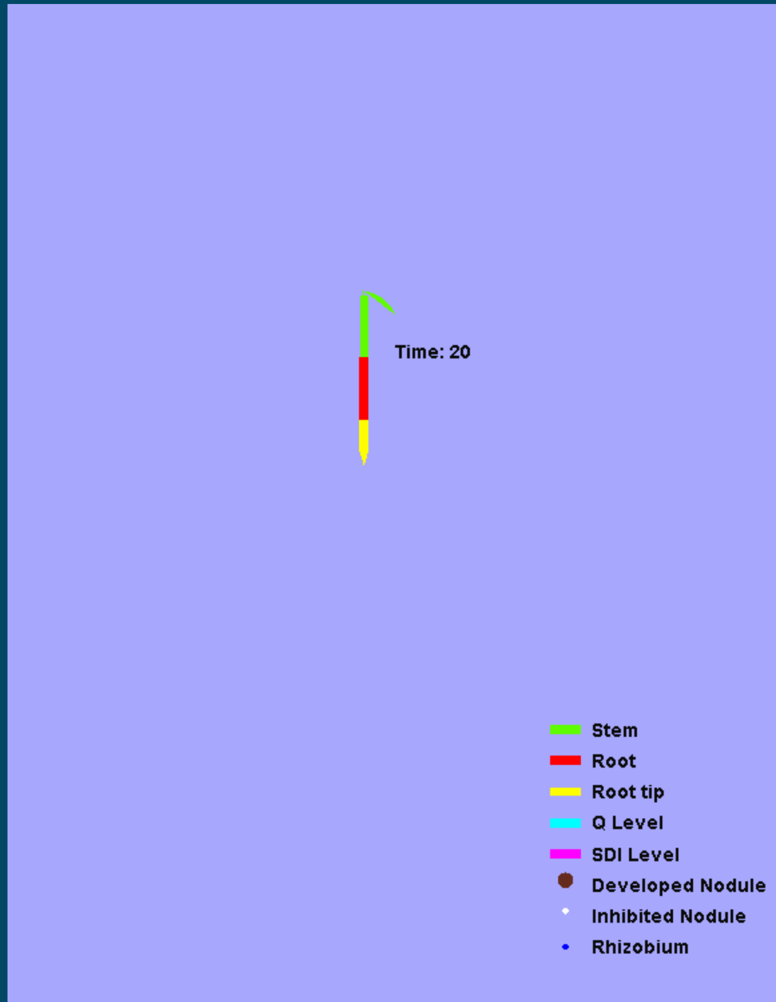
- L-systems (Lindenmayer): grammars for plant growth
  - elements include: stem segment (& length), bud, leaf branch (& angle), root segments, root nodules
  - production rules which include gene factors & signals



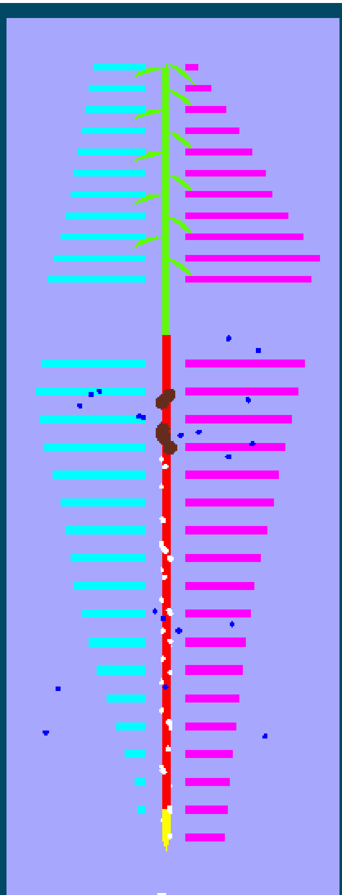
Root nodules in legumes

Model includes:
- GRN in root cells
- GRN in shoot cells
- signals between roots & shoots (Q, SDI)

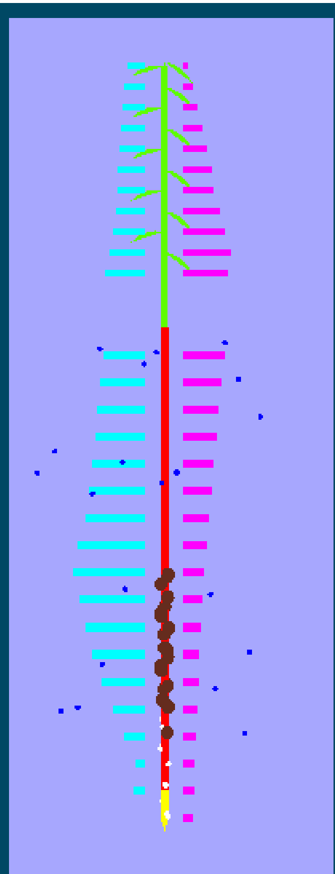
Nodule formation occurs when bacteria present & SDI level low



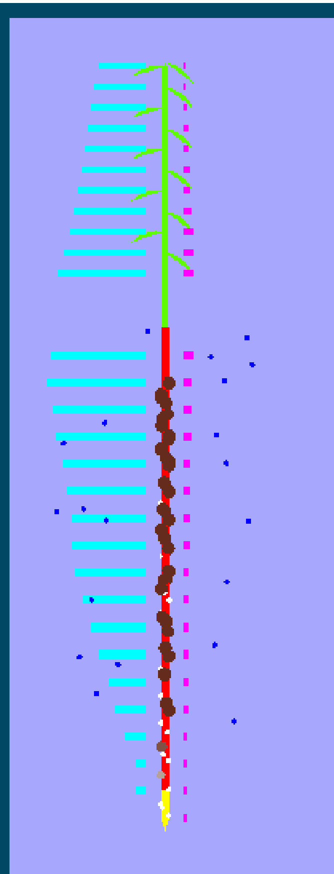
Nodulation behaviour



Early Inoculation



Late Inoculation



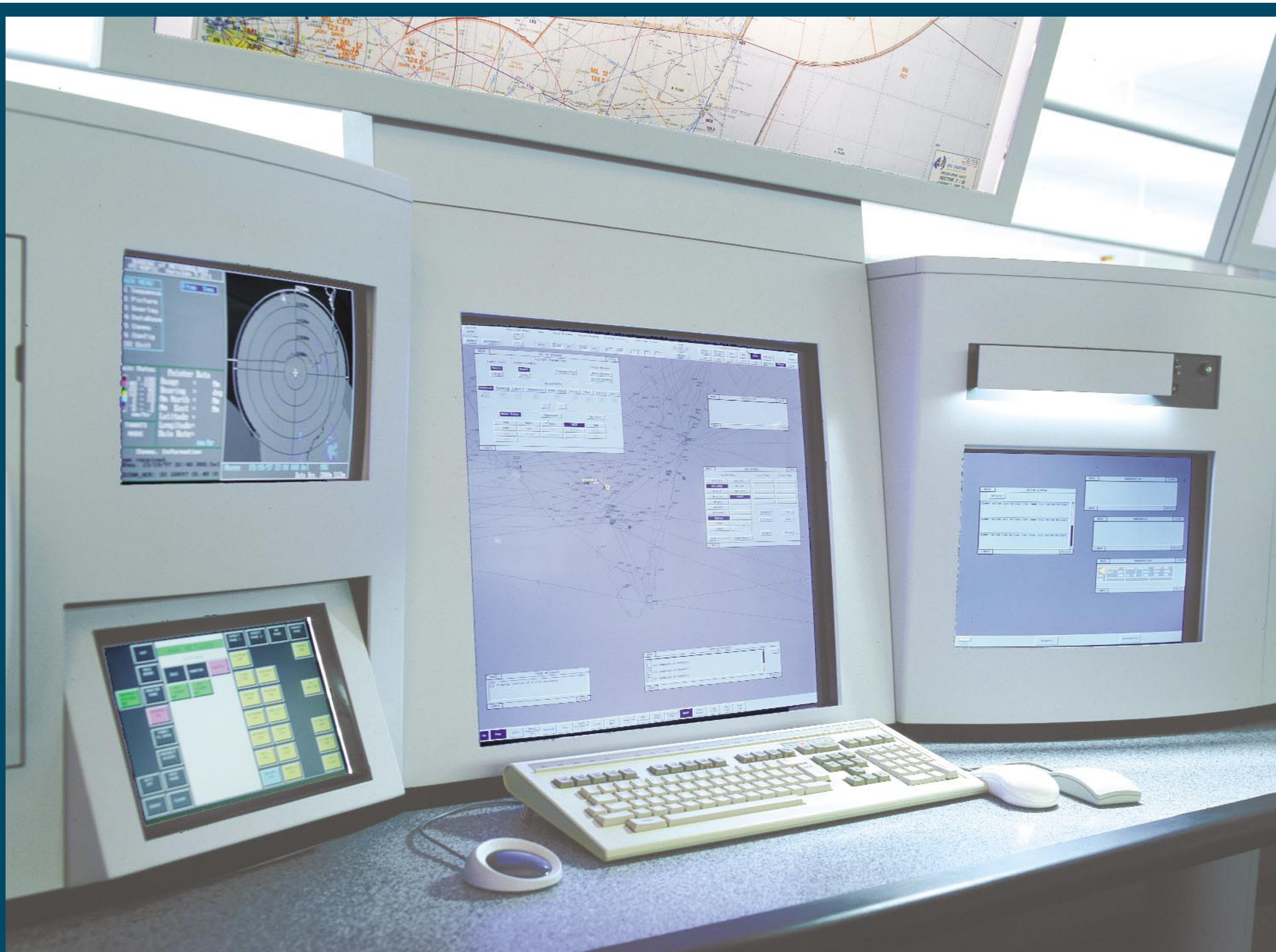
NARK mutant

Outline of talk

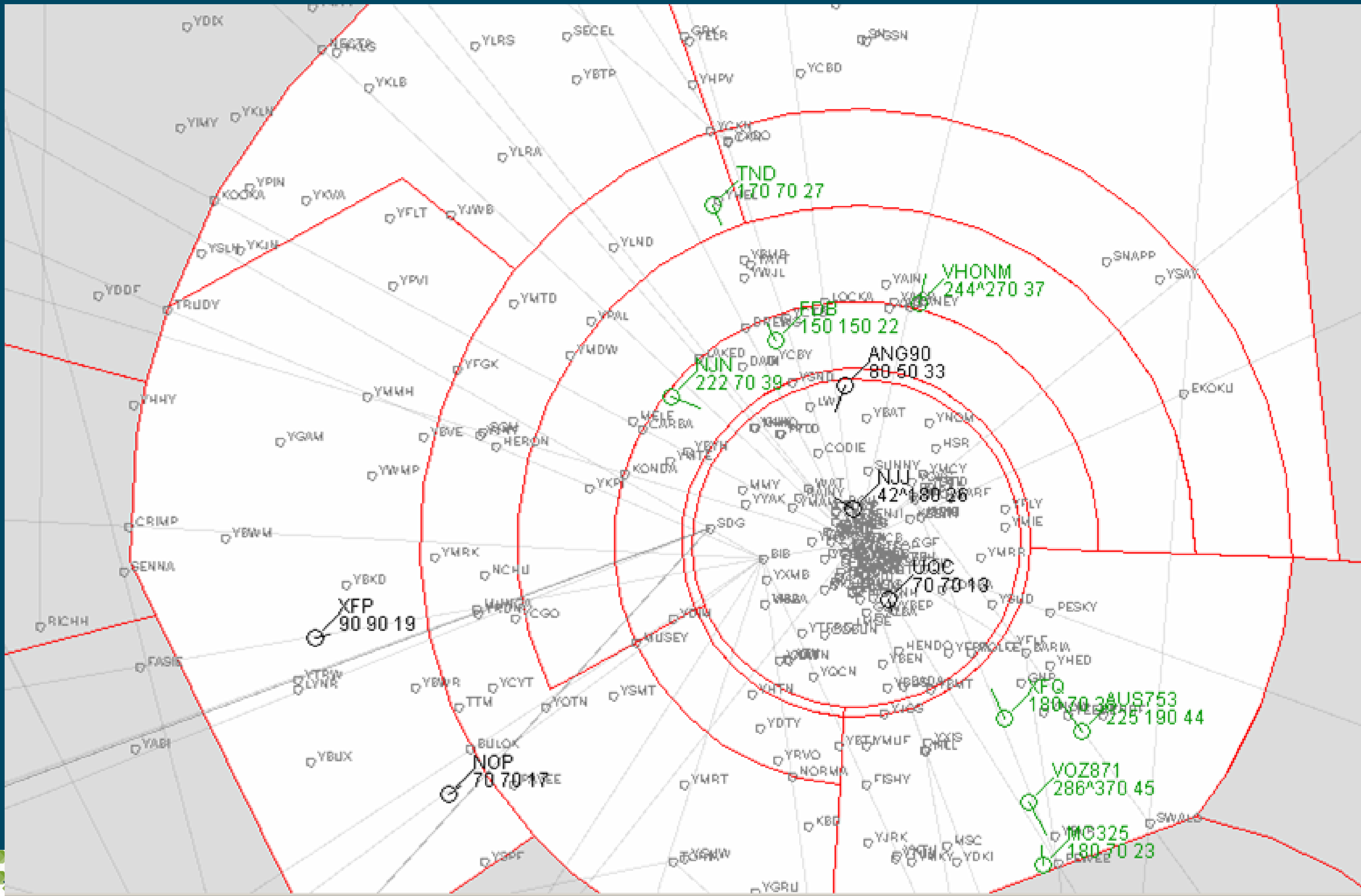
- About the ARC Centre for Complex Systems
- Genetic Regulatory Networks
- Free Flight Air Traffic Control
  - or rather, freer flight = more user involvement
    - distribution of (some) control to aircrews/airlines
      - User Preferred Trajectories (UPTs)
  - Terminology, trends & challenges
  - ATC as a complex system
    - Multi Agent System models
    - Boids & flocking behaviour
  - 3 research projects modelling new ATC operational concepts

Air Traffic Control in the past(?)

ATC in Australia



An ATC sector at a quiet time



ARC CENTRE FOR COMPLEX SYSTEMS

Terminology & concepts

- En-route flight phase: > 100km from airports
- Different separation standards apply: eg
  - Lateral: 5NM horizontal distance (~9km)
  - Vertical: 1000’ (~300m)
  - Longitudinal (aka “in trail”): 30NM when on same path
    - 100NM when no radar
- Separation violation: the separation standard is not met
- Trajectory: 4D object, including route, height & time at waypoints

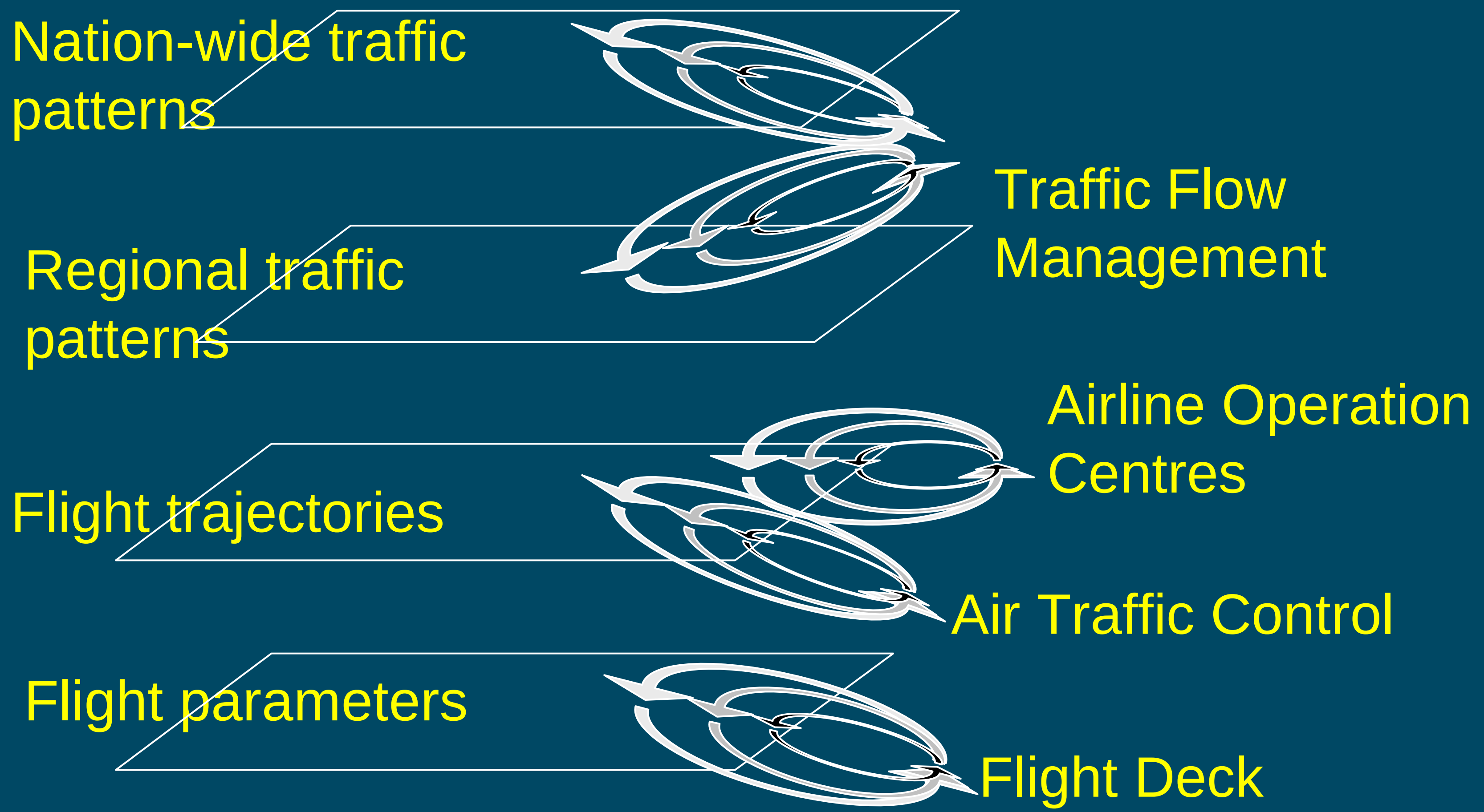
ATM trends & challenges

- Changing nature of Air Traffic Management:
  - Australian system now entirely computer-based
  - ADSB will enable radar-like surveillance of whole continent
  - improved navigation via GPS
    - routes no longer need to be fixed
    - “Flex tracks” enable taking advantage of tail winds
  - Datalink communications will enable interchange of trajectory information
- Goal: User Preferred Trajectories
  - choose own route, height, speed

Advantages of UPTs

- Significant savings are possible if airlines can choose their own trajectories
  - eg fuel use, emissions, flight time
  - airlines can optimise to suit their own operational imperatives
    - fuel use, arrival time, manoeuvring, …
- But UPTs is a major change in operational concept, with many research issues
  - 15 year lead time
  - 5 ConOps, 5 functional architecture, 5 test & prove

Airspace as a complex system

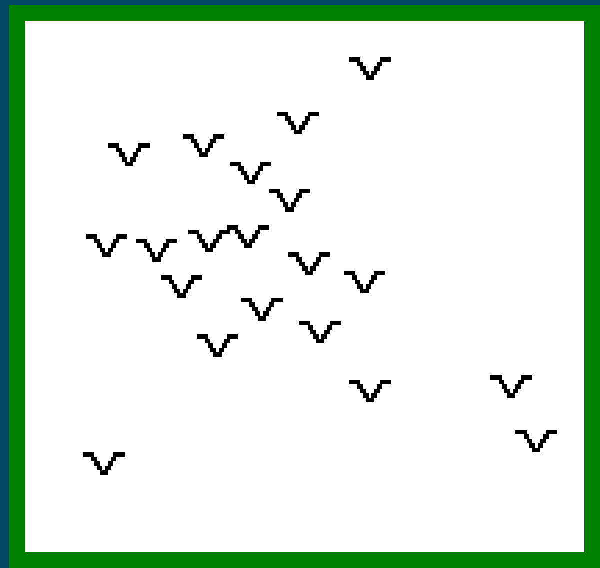


Emergent properties in this case are safety, efficiency, orderliness, predictability,…

ARC CENTRE FOR COMPLEX SYSTEMS

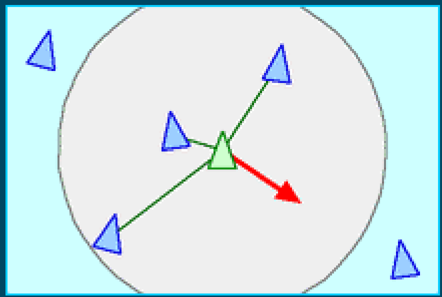
Flocks of aircraft?

- One way to reduce controller workload would be to have aircraft fly in a cluster
  - “Moving sectors”
  - Aircraft do their own separation assurance within the cluster
  - Possible application of flocking behaviour?
- Flocking behaviour has been reduced to 3 simple rules:

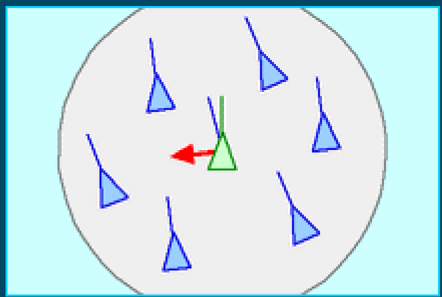


ARC CENTRE FOR COMPLEX SYSTEMS

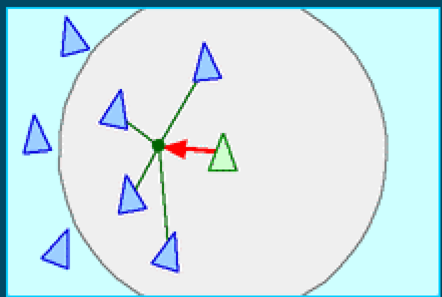
3 simple steering behaviours



Separation: steer to avoid crowding local flockmates



Alignment: steer towards the average heading of local flockmates



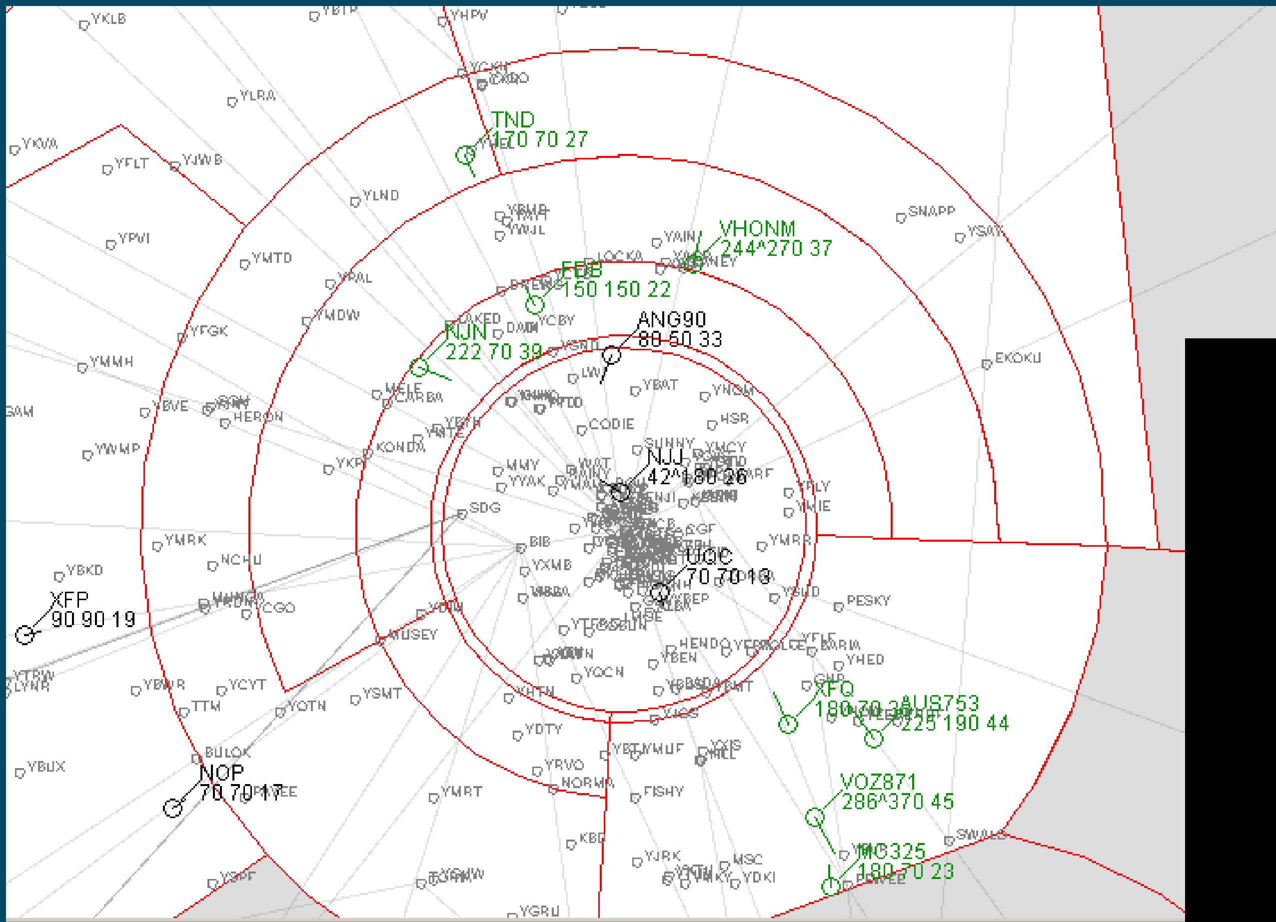
Cohesion: steer to move toward the average position of local flockmates

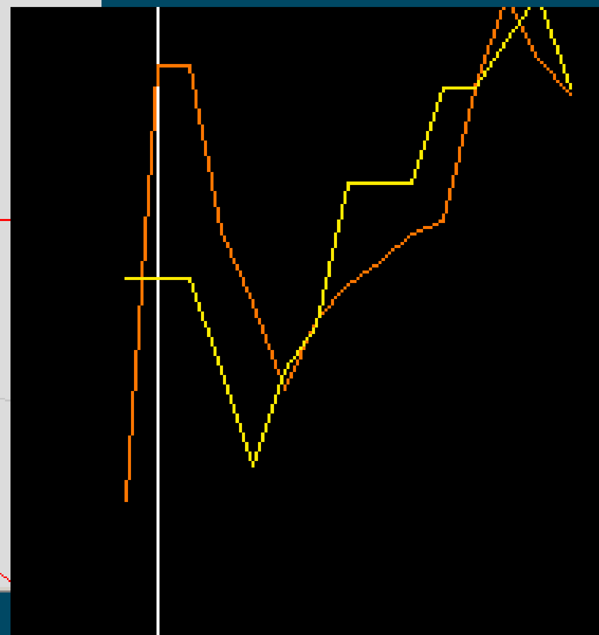
From Reynolds on Boids

3 example projects

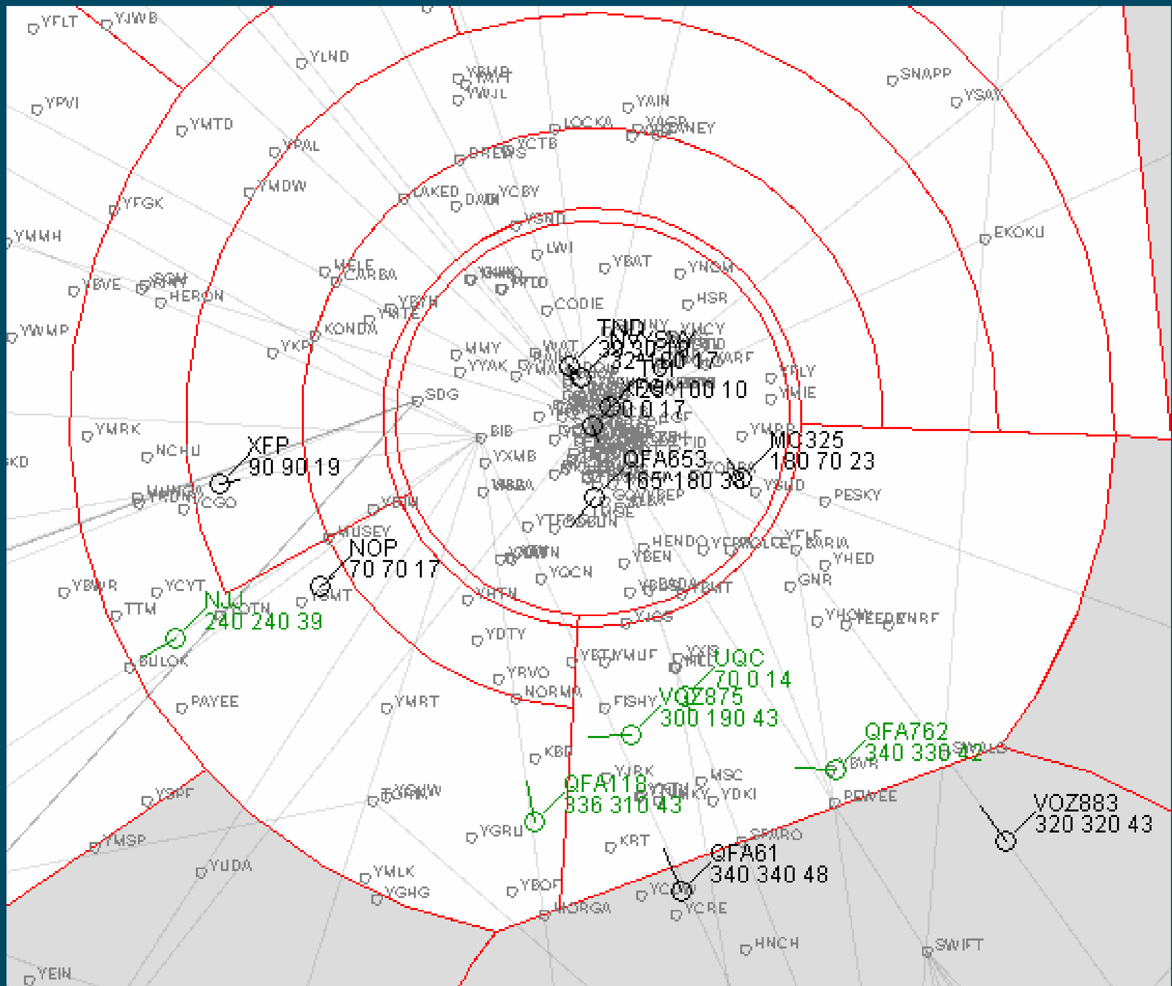
- ATC Workload:
  - With Airservices & UQ's Human Factors Key Centre
  - Aim: To develop a model that can:
    - Measure the flow of traffic through an air sector
    - Define a measure of traffic complexity ("workload")
    - Predict the level of workload that an average controller will experience
  - The challenge: to model the effect of controller interventions on traffic
    - Also, controllers adapt their behaviour to moderate future workload
  - Model will be used for inform design of new airspaces & for dynamic reconfiguration of airspaces

Ex 1: Medium workload, about to decrease



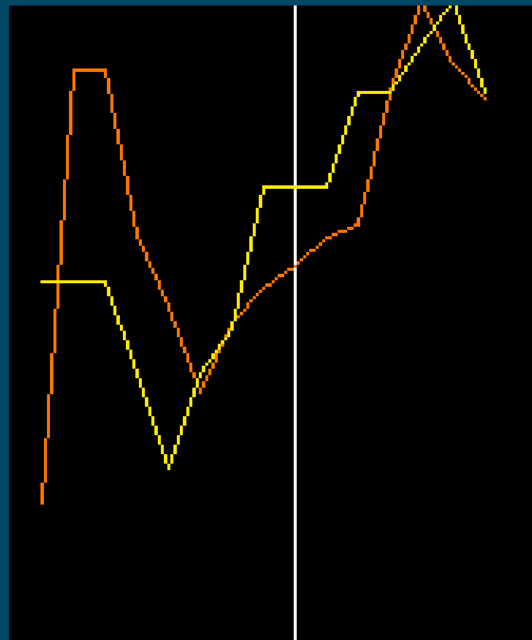


Ex 2: Medium workload, about to increase



Workload rating

Number of aircraft



Project 2: Moving sectors

- A methodology for training teams of agents
  - PhD project (KY Chen)
  - Problem is: how to discover the rules that agents should follow, so that they optimise their own objectives while simultaneously optimising overall team objectives
  - Case study 1: what trajectory should an aircraft fly, if it wants to join a moving sector
    - Assume all trajectories are published
  - Methodology is Learning Classifier Systems
    - Evolutionary rule learning

ARC CENTRE FOR COMPLEX SYSTEMS

Project 3: trajectory-based ATM

- Aim: develop a more detailed concept of operations for trajectory-based ATM
  - …where UPTs are the default,
    & interventions are the exception
- Key research questions:
  - How to move from distance-based ATM to time-based trajectory management?
  - What is the appropriate functional architecture?
  - What real-time support can be provided to AOCs to produce trajectories that are safe & mutually optimal?

Summary & conclusions

- ARC Centre for Complex Systems
  - Focus is on network-based systems
    - Simple agent behaviour + interactions = complex system behaviour
  - 3 application areas: GRN, ATC, Evolutionary economic systems
  - Methods & tools for understanding, managing & controlling complex systems

Summary (2)

- Genetic Regulatory Networks:
  - 2 levels of agents:
    - genes with states *on/off* (gene expression)
    - Cells, with gene expression sets
  - interactions (m:1):
    - send chemical signals to neighbouring cells
    - turn a gene on or off (regulate)
  - System behaviour = ontogeny (cell lineage); development of growth & form

Summary (3)

- Air Traffic Control:
  - agents = aircraft (/airlines) & ATCo's
  - agent behaviour = 4D trajectory
  - interactions: avoid violating separation
  - system behaviour = traffic complexity (workload)

ARC CENTRE FOR COMPLEX SYSTEMS

Summary (4)

- Nature can give us inspirations
- Modelling & simulation has many advantages over experimentation
  - But generally not possible to validate models quantitatively
  - Instead “validity” means: does it yield new insights

Acknowledgements

- Genetic Regulatory Networks program:
  - Janet Wiles – leader
  - Jim Hanan – plant models
  - Nic Geard – *C.elegans* models
- Air Traffic Control program:
  - ATC Workload project is a collaboration between ACCS, UQ's Key Centre for Human Factors & Applied Cognitive Psychology & Airservices Australia
  - Andrew Neal, Project Leader
  - Penny Sanderson, Scott Boland, Ariel Liebman,…
- Plus many more

ARC CENTRE FOR COMPLEX SYSTEMS