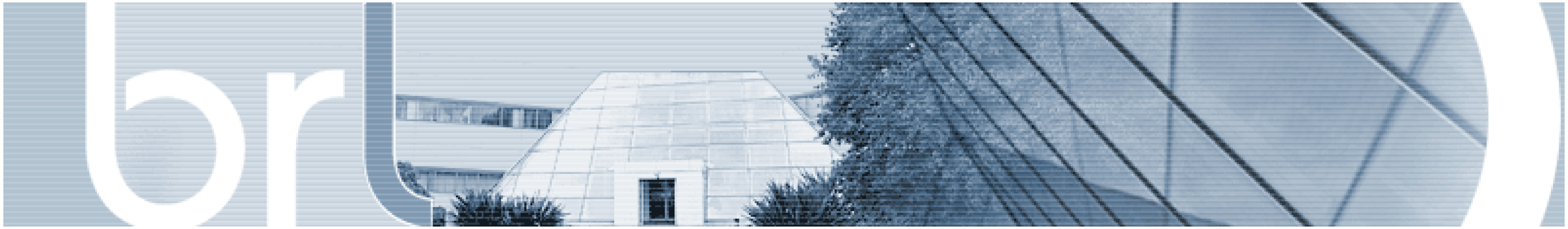

Swarm Engineering for Real-world applications

out of the lab and into the real world

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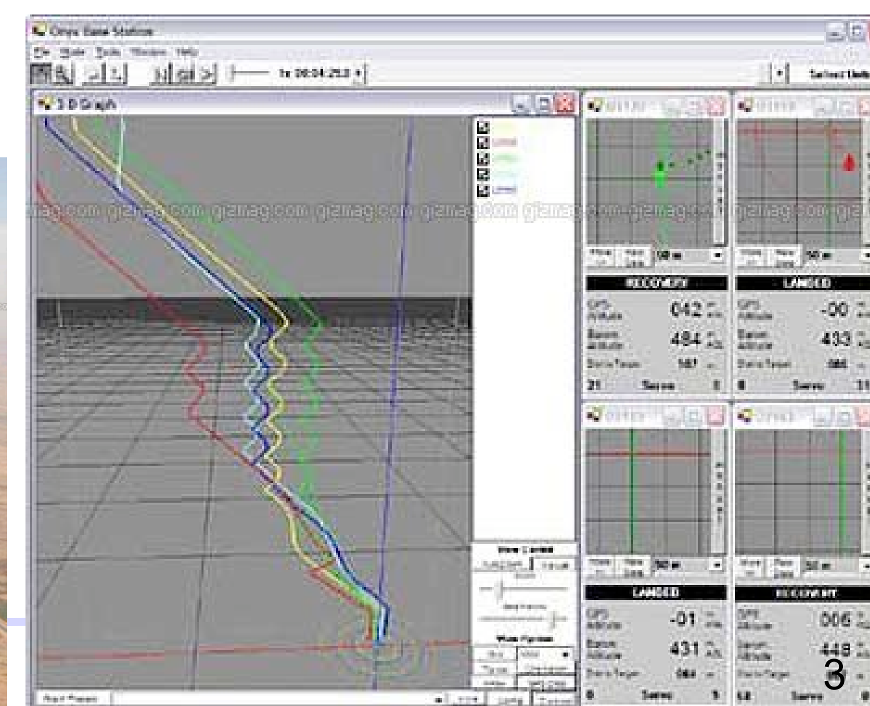
This Talk

- The problem of taking swarm robotics from the laboratory into the real-world
  - How can we design swarm intelligence in a methodologically rigorous way?
  - Swarm Engineering
- In four parts:
  - (Structured) Swarm Engineering
  - Failure Modes and Effects Analysis (FMEA)
  - Reliability Modelling
  - Swarm system test and verification

Real-world Applications

- At the time of writing there is only one known real-world application of swarm robotics
  - A swarm of autonomous parachutes for delivering supplies
    - the *Onyx* parachutes swarm to maintain proximity so that they will not be widely dispersed on landing
    - see http://www.gizmag.com/go/6285/



What is a *Dependable Swarm*?

- It is a complex distributed system, designed using the *Swarm Intelligence* paradigm, which meets *standards* of analysis, design and test that would give sufficient confidence that the system could be employed in critical applications
  - Q: What are these standards?
  - A: They don't exist
- The purpose of our current work is to develop a framework for the analysis, design and test of dependable swarms
- I call this framework *Swarm Engineering*

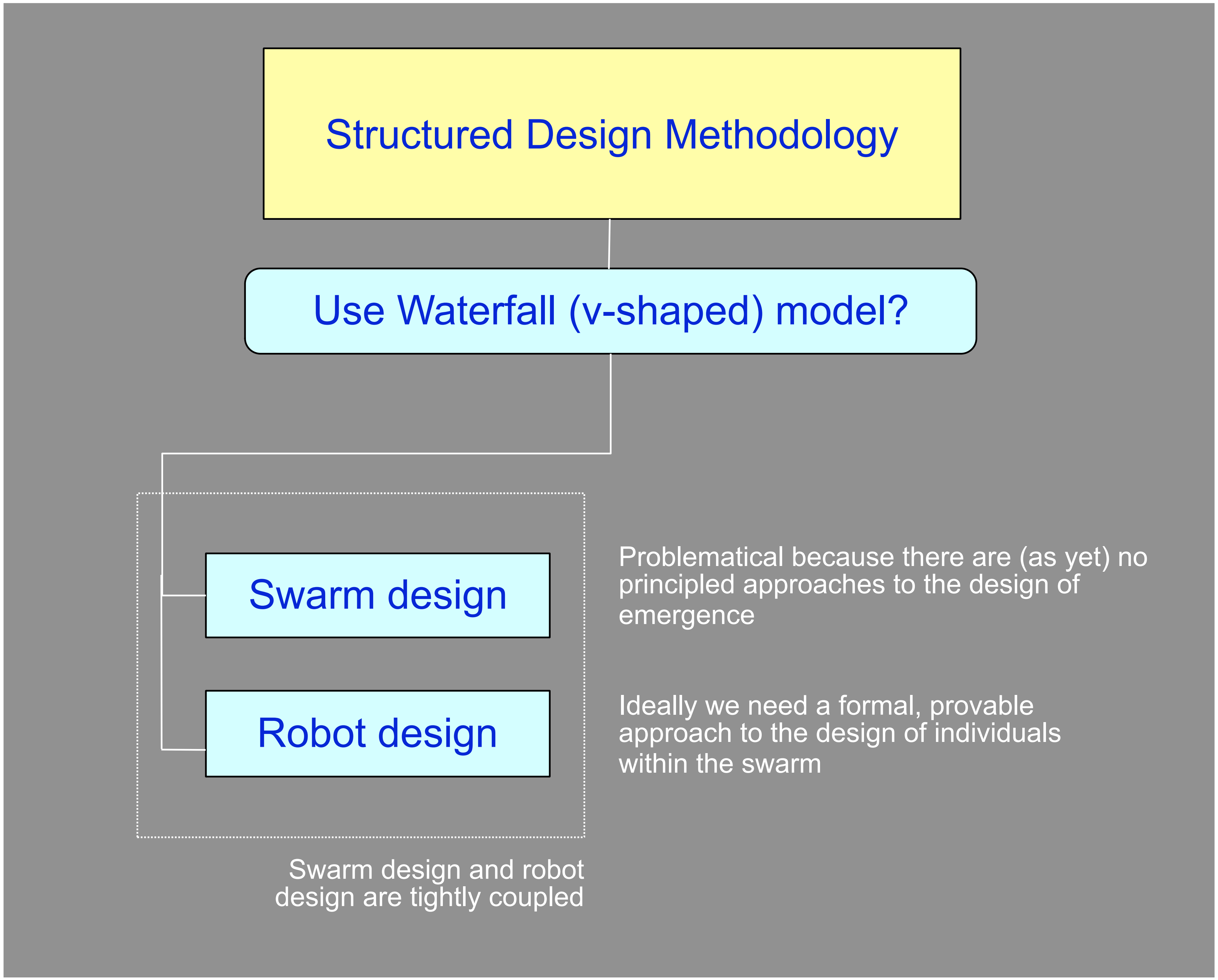
Winfield et al, LNCS 3342, 2005

Assurance of Dependability

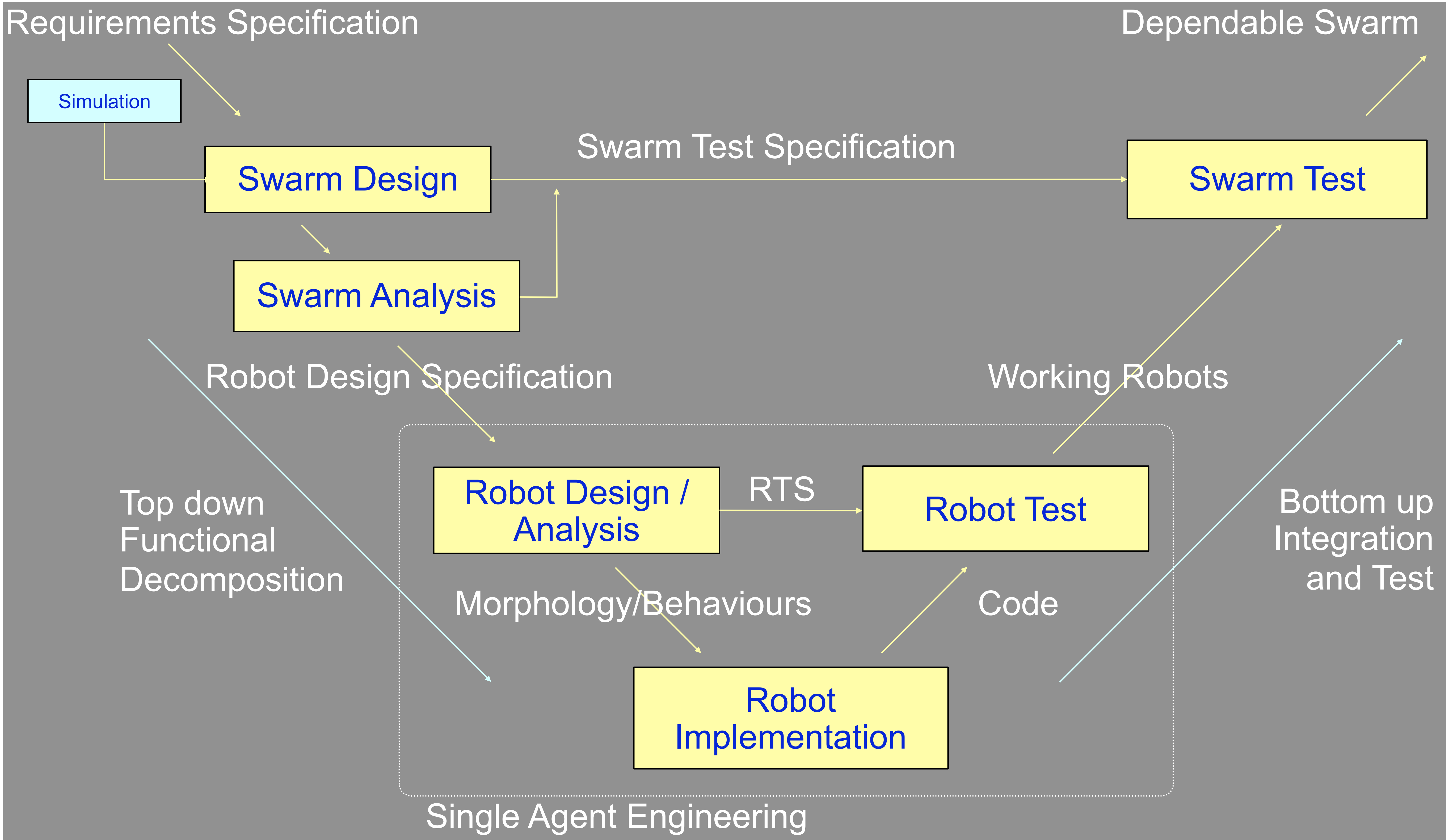
Analysis | Design | Test

- What makes swarm engineered systems different?
  - System functionality achieved through emergence
  - Swarms are dynamical, stochastic, non-linear systems
  - *Task completion* becomes very hard to define.

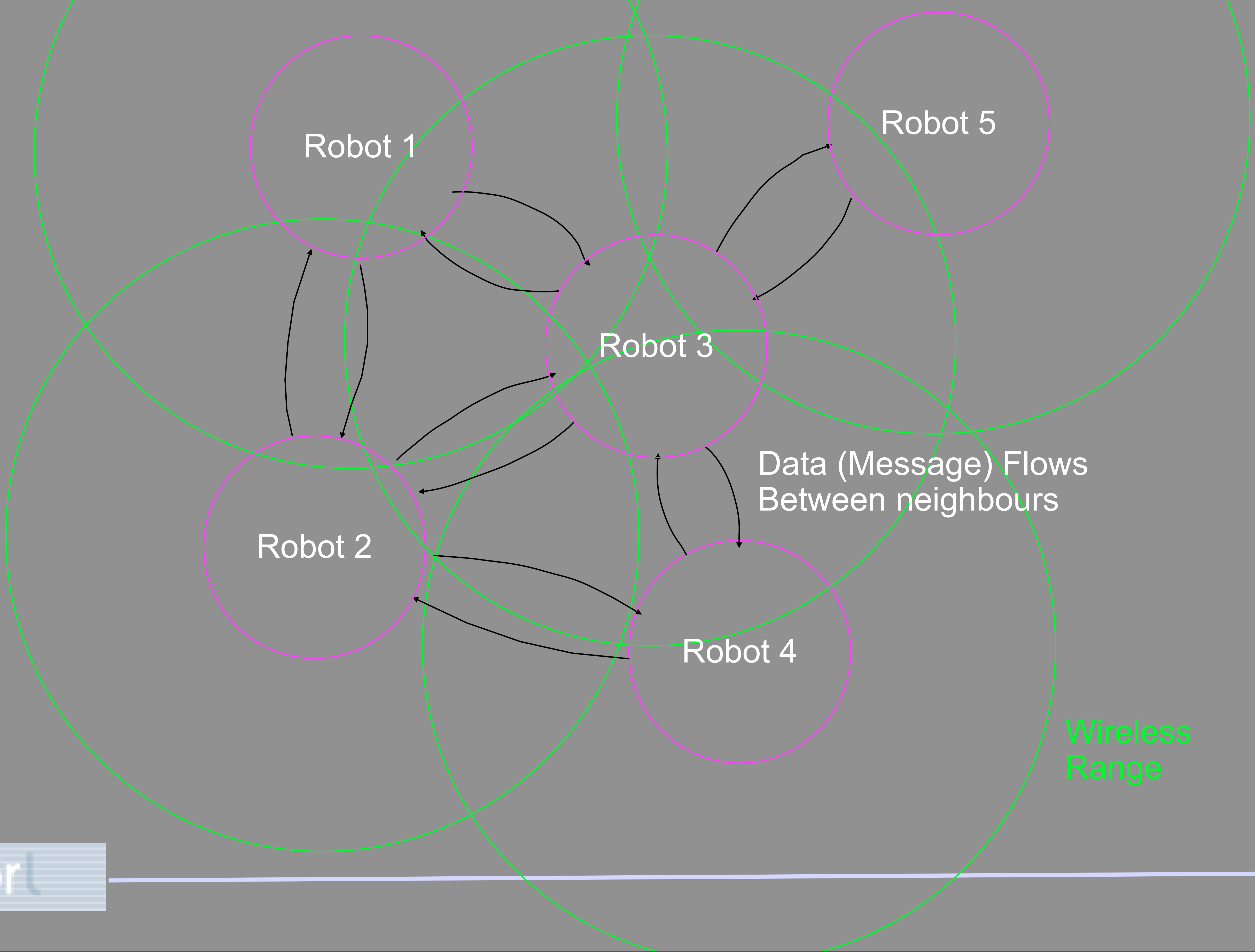
Designing the Swarm



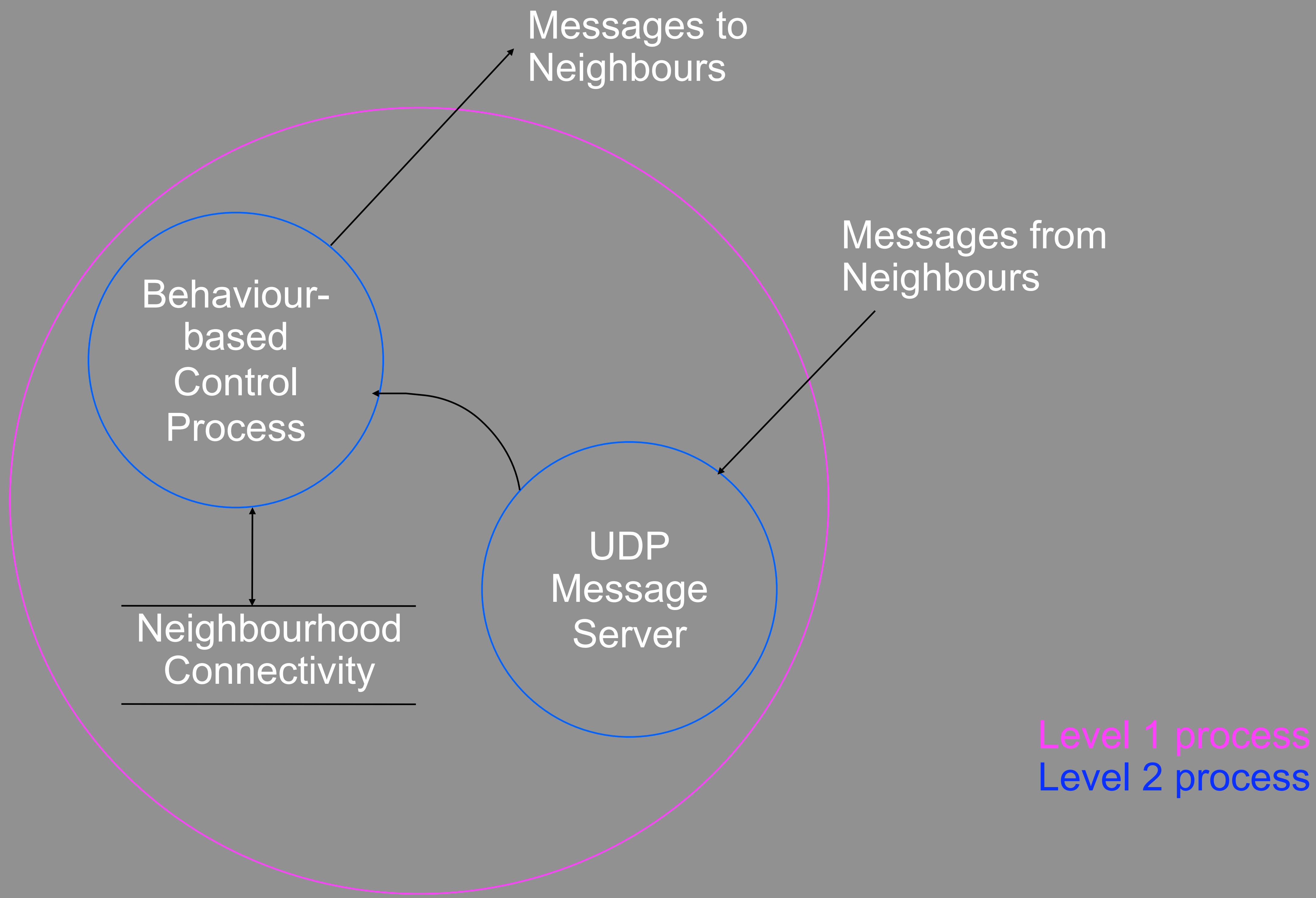
(Structured) Swarm Engineering



(Dynamic) Data Flow Diagram

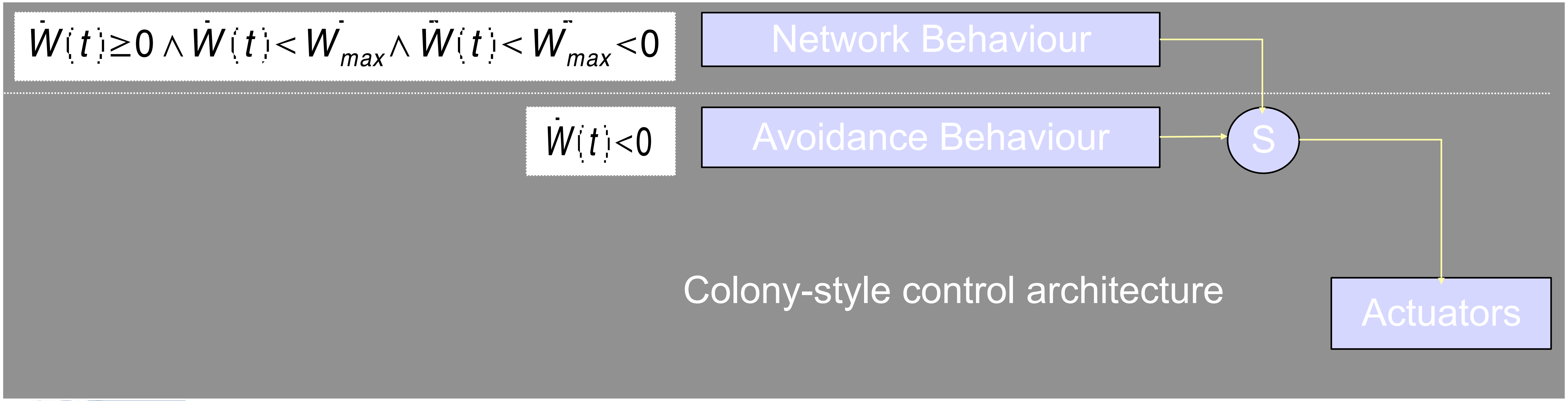


Single Robot Processes



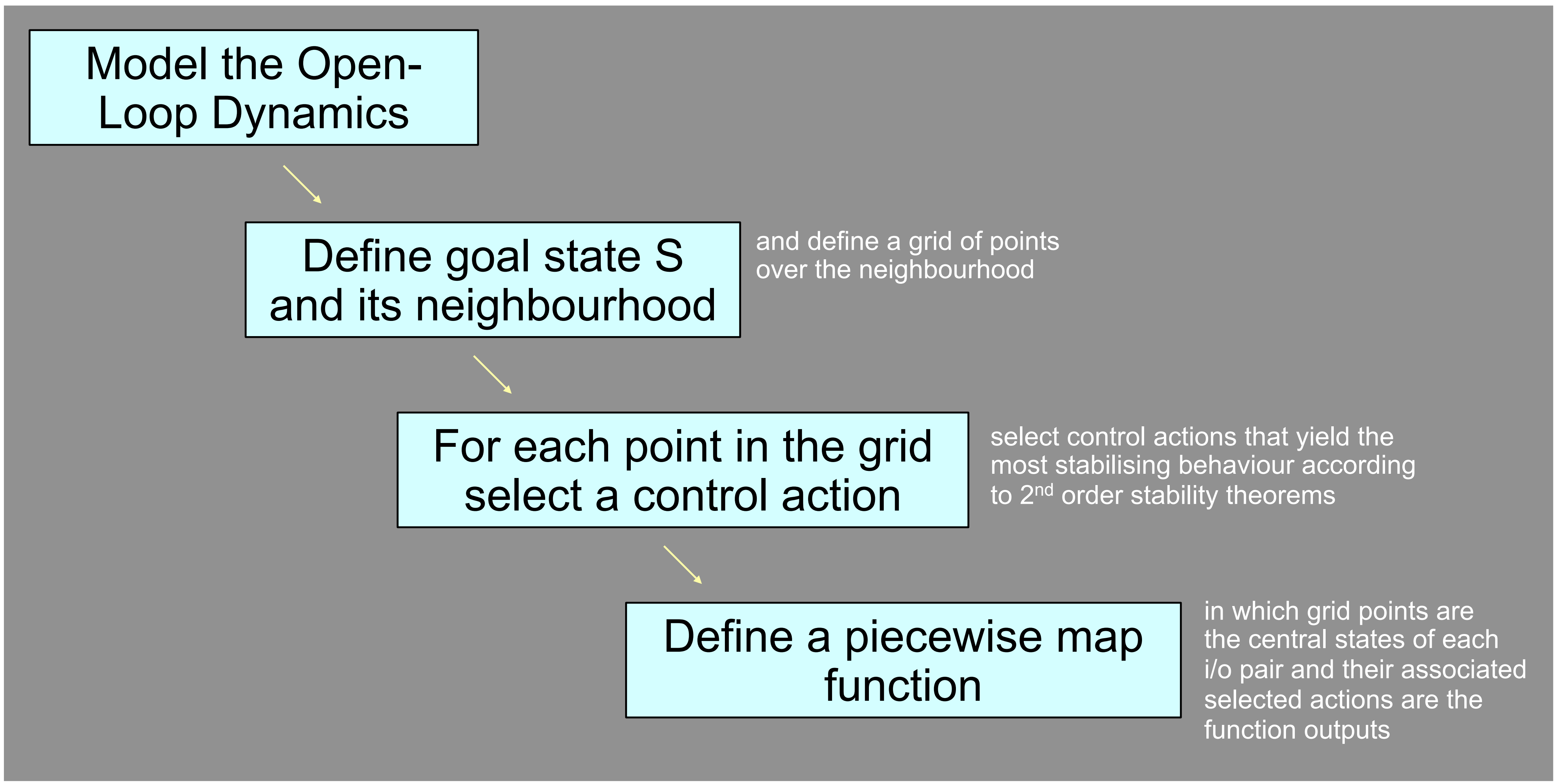
Provably Stable Behaviour-based Control

- We extend Lyapunov stability theory to second-order stability theorems
  - then use the partial subsumption relationship between the 1st and 2nd order Lyapunov stability theorems as the basis for a formal model of the subsumption architecture

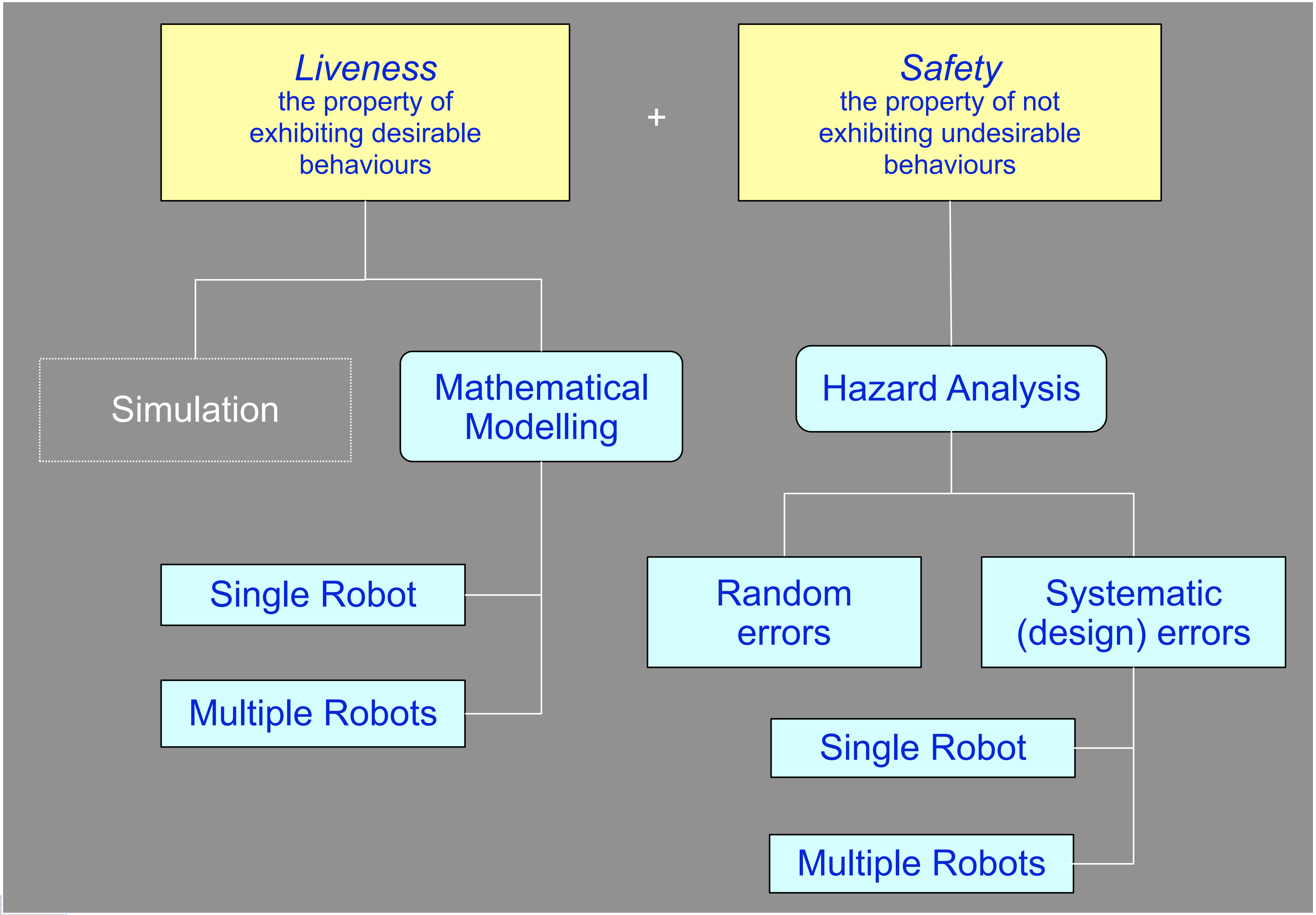


Direct Lyapunov Design

- We use the 2nd order Lyapunov stability theorems as the basis for a design procedure for the motor schema of a behaviour module



Swarm modelling and analysis

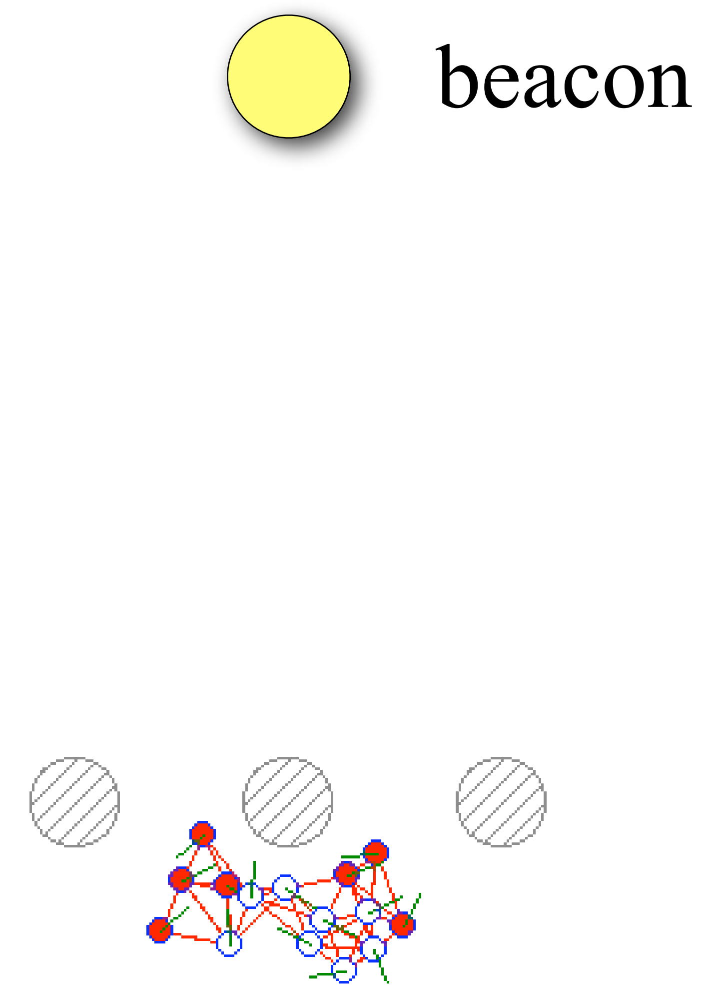


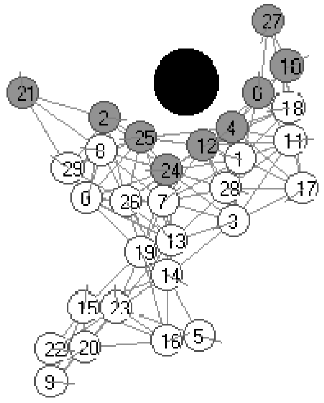
Failure Modes and Effects Analysis

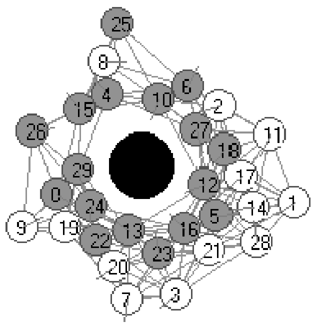
- Enumerate each possible hazard:
  - internal and external (environmental)
- Consider the effect of each hazard on each swarm behaviour
- For our swarm robot system there are no system-wide components or structures
  - thus we need to consider only individual robot internal faults

Case Study: Swarm Containment

- Swarm taxis towards a beacon
- Introduce occluding obstacles
  - The swarm finds it way between the narrow obstacles
- Beacon containment...







Single robot: failure modes

Hazard	*Description*
H1	Motor failure
H2	Communications failure
H3	Avoidance Sensor failure
H4	Object Sensor failure
H5	Control Systems failure
H6	All Systems failed

Failure Effects

	Failure Effect
E_1	Motor failure impedes the translational motion of the swarm (anchors the swarm)
E_2	Lost robot(s) loose in the environment
E_3	Robot collisions with obstacles or target

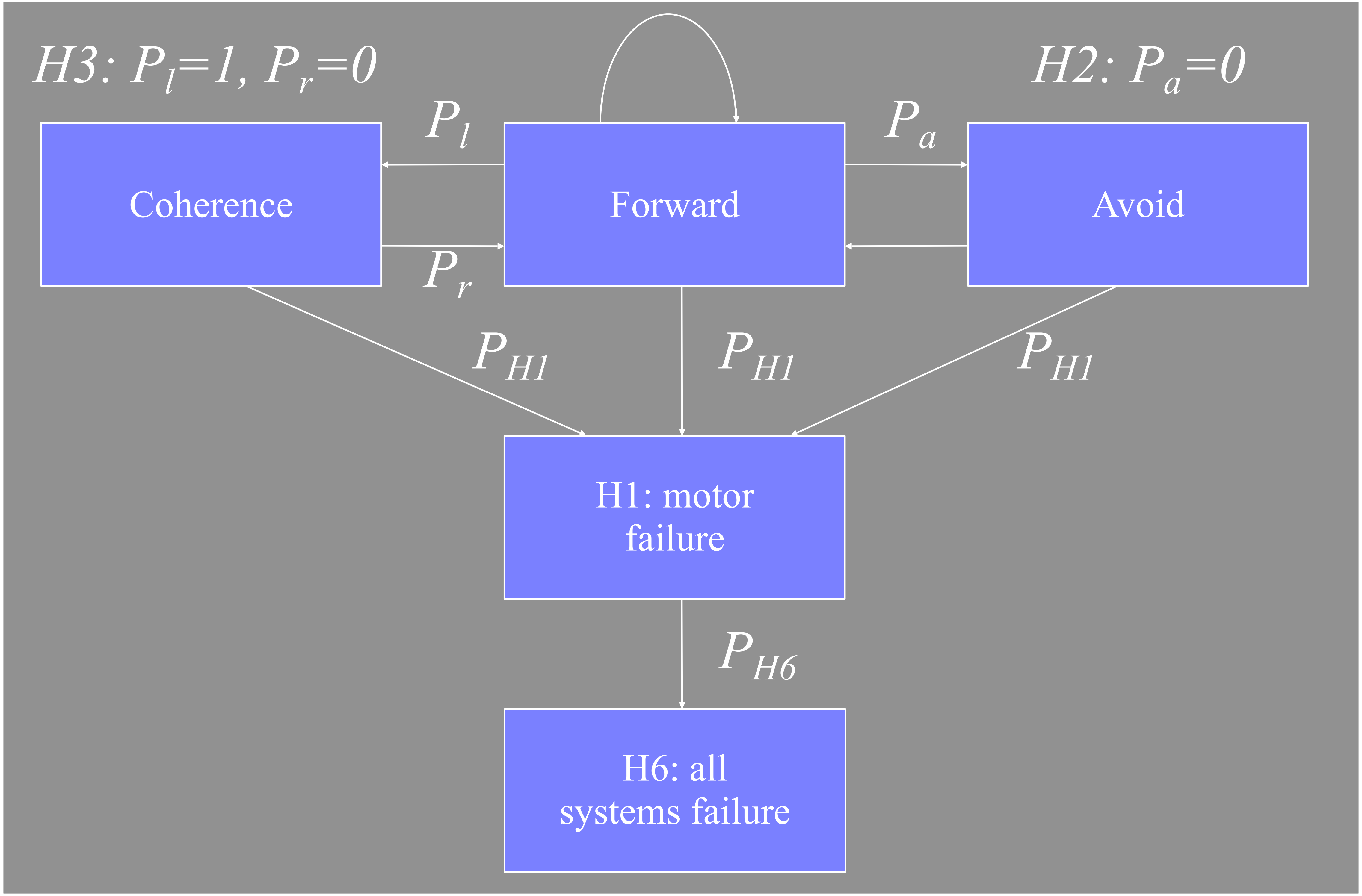
Failure Modes and Effects

Swarm Behaviour	H_1	H_2	H_3	H_4	H_5	H_6
Aggregation	-	E_2	-	-	E_2	-
Ad-hoc Network	-	E_2	-	-	E_2	-
Object Taxis	E_1	E_2	-	-	E_1	-
Obstacle Avoidance	E_1	E_2	E_3	-	E_1	-
Object Containment	E_1	E_2	E_3	-	E_1	-

Swarm FMEA conclusions

- Counter-intuitively, partial robot failures are much more serious than complete robot failure
  - dead robots are simply regarded by the swarm as objects in the environment to be avoided
- One mission-critical failure mode: motor failure
  - because it anchors the swarm, hindering movement toward the object to be contained
- Possible remedies:
  - robot's monitor own motor status, or
  - bio-inspired swarm auto-immune response

FSM with hazards..?



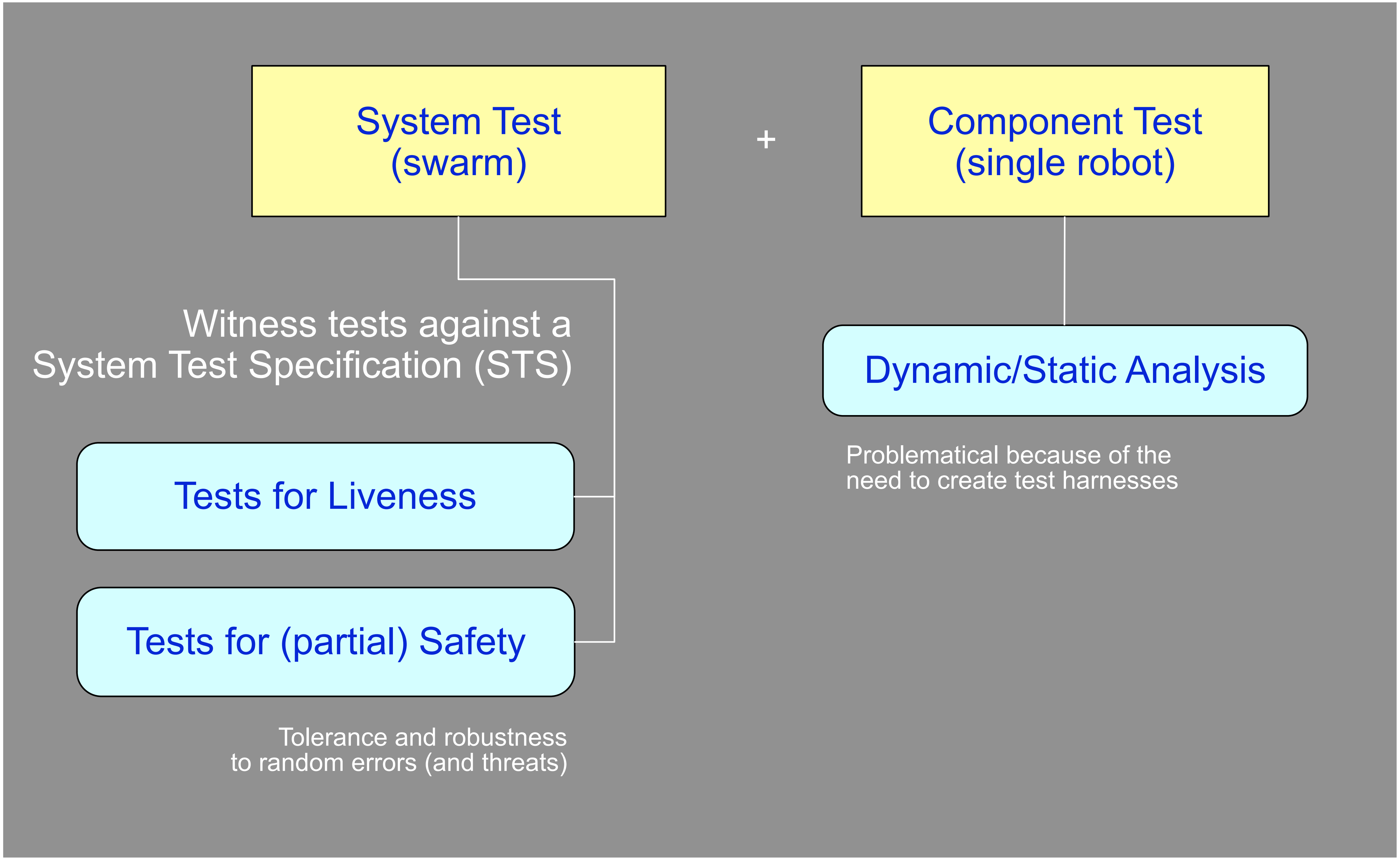
Swarm Reliability Modelling

- Modelling the reliability of a swarm appears straightforward, since it consists of N identical agents operating in parallel
  - For a parallel system of N robots with independent probability of failure p, reliability R
  - $R = 1 - p^N$

Multi-state reliability

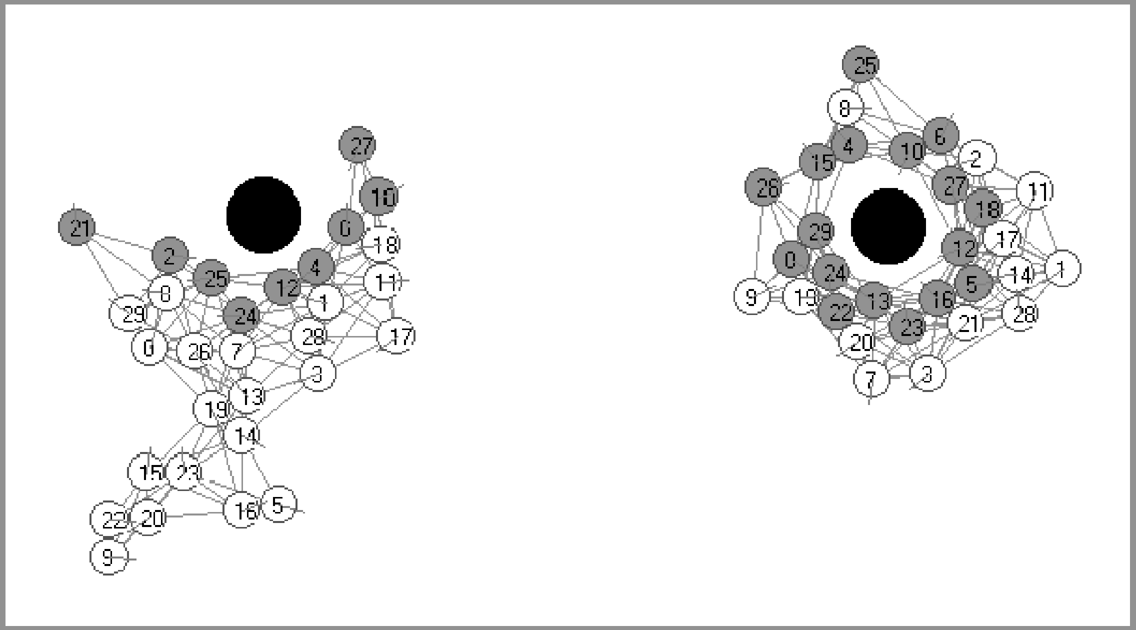
- however, FMEA shows us that individual agents could be in partially failed states thus, for our case study
  - $R = (1 - p_1)^N - p_6^N$
  - where $p_1 = P(H_1)$ and $p_6 = P(H_6)$
- but emergent swarm behaviours require as least *K* operational agents
  - thus reliability modelling requires a *multi-state k-out-of-n* approach

Testing the Swarm



Testing the swarm

- We need to
  - establish robust measures for achievement of desired (emergent) behaviours, then
  - define (statistical) test for these measures

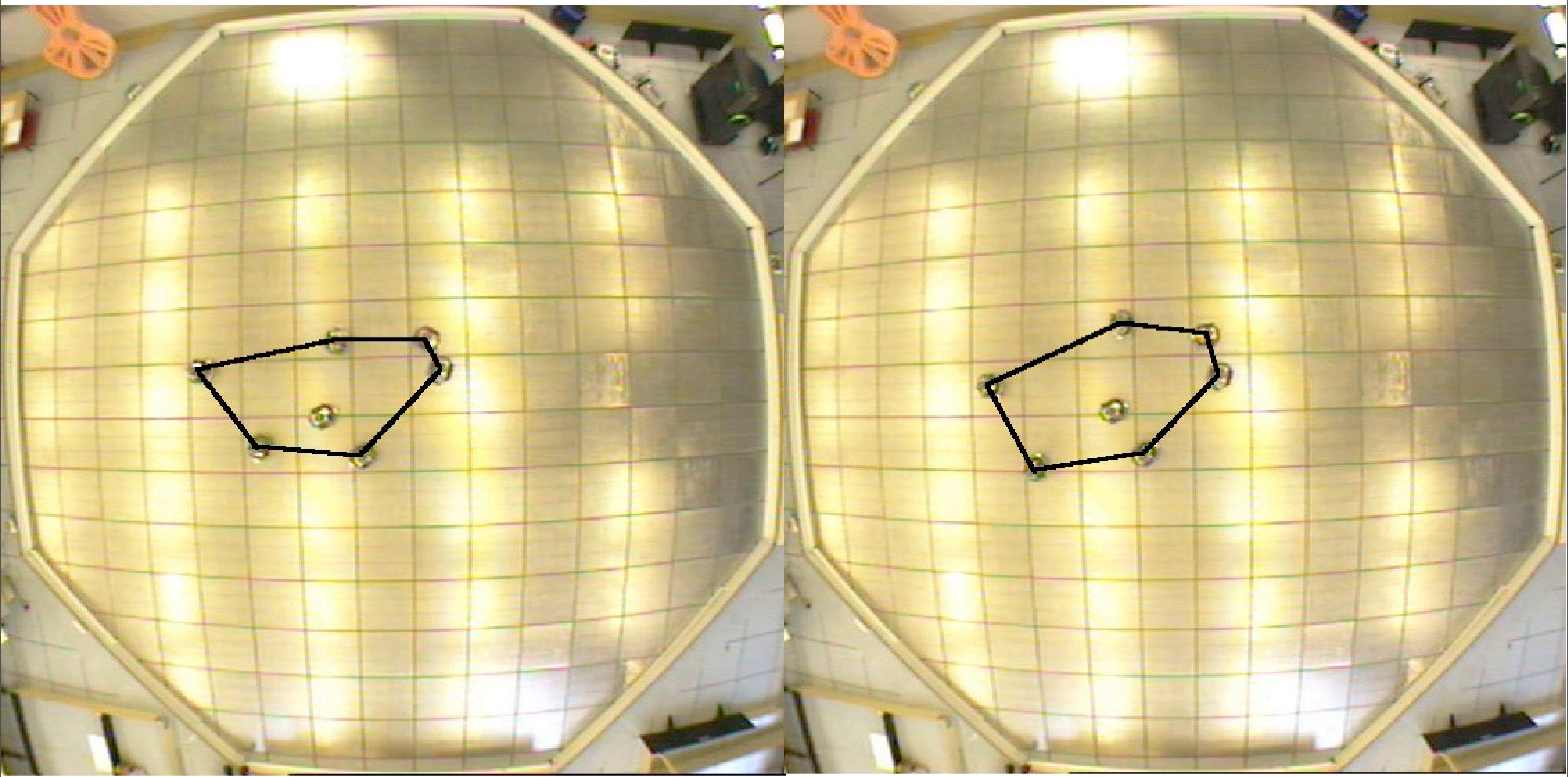


V_s – Mean swarm velocity toward target

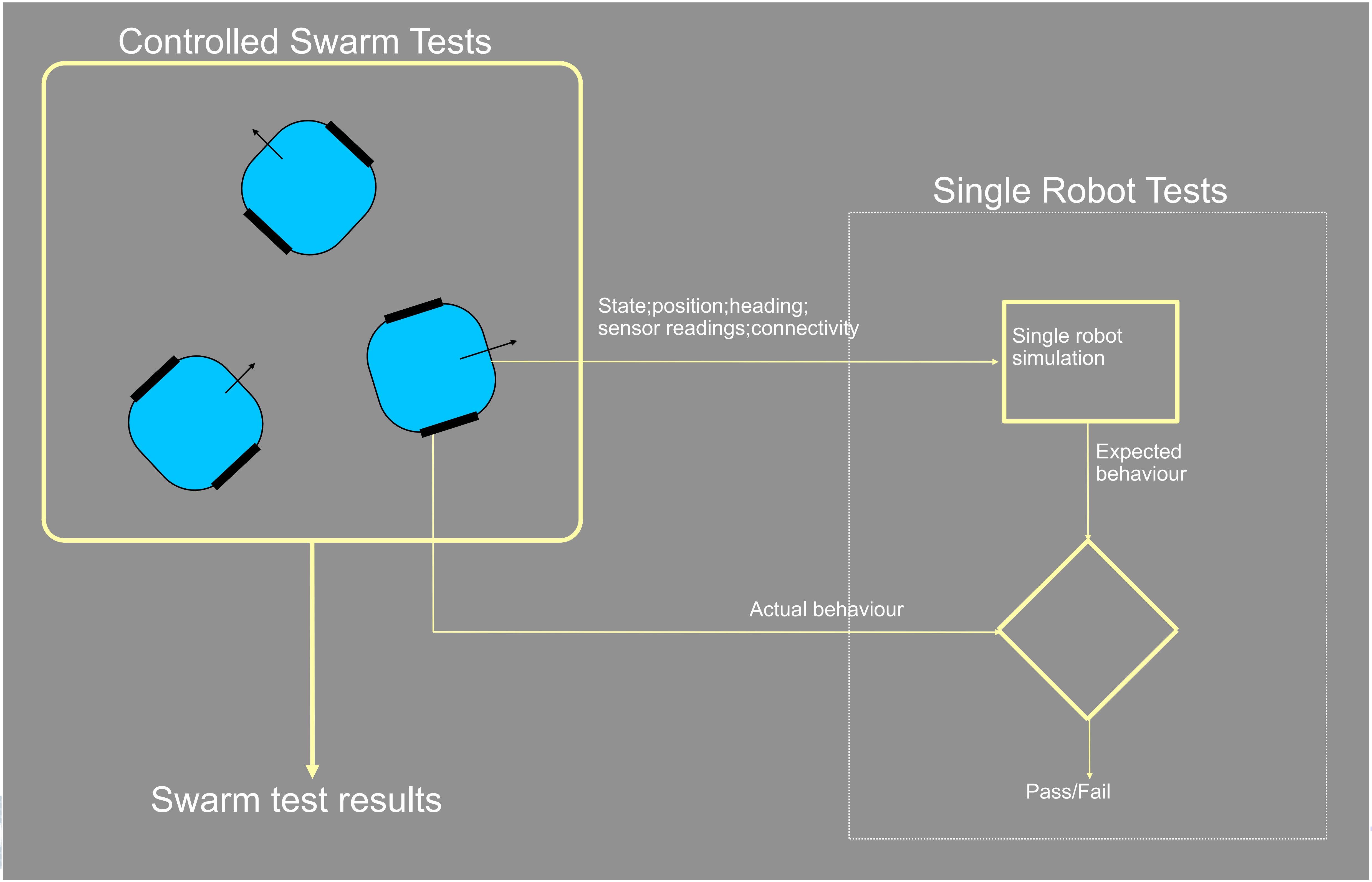
Q_e – Mean quality of encapsulation
R_e – Mean radius of encapsulation

Frequency that $Q_e > Q_{threshold}$ in a given time period for given starting conditions

Swarm Tests in progress



Swarm tests can provide an *environment* for single robot test



A roadmap towards swarm engineering

- Substantial work is needed before dependable swarms can become reality
  - We need to extend and strengthen analytical approaches to modelling of swarm systems
  - We need to extend and strengthen formal approach to provably stable intelligent control
    - To include safety as well as liveness
  - We need a more principled approach to the design of emergence
  - We need to start work on 'safety' analysis at the swarm level
  - We need to develop metrics, methodologies and practices for the testing of swarm engineered systems

Discussion

- But... can or should we really think about classical approaches to system validation in the context of swarm engineering?
  - some in classical safety systems believe the standard approach is already breaking down for very complex (conventional) systems
  - perhaps a new engineering paradigm calls for new approaches to dependability?

Conclusions

- A swarm engineering approach to the design of large-scale distributed systems could lead to systems with very high levels of intrinsic fault tolerance, and scalability but *without special effort by the system architect*

Winfield, Harper & Nembrini, Proc ICSS, 2006