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A new paradigm for dynamical modelling of networked C2 processes

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13th ICCRTS "C2 for Complex Endeavours"
Seattle, WA, USA, 17-19 June 2008

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Modelling C2 for Complex Endeavours

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Complex Endeavours
Alberts & Hayes, 2007

- **National/Strategic level(s)**
- **Military/Strategic level(s)**
- ***Interagency/Coalition levels/NGOs***
- **Military Operational (HQJOC, Theatre Command, JTFs)**
- **Tactical (Combat/Humanitarian/Peacekeeping actions)**
- **Complex Networking of these systems.**

- *Can one model integrate all of these?*
- *Can outputs at one level **be commensurate** with inputs required at another level?*

- ***Look for universality across levels.***

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C2 Processes: they're all cycles!

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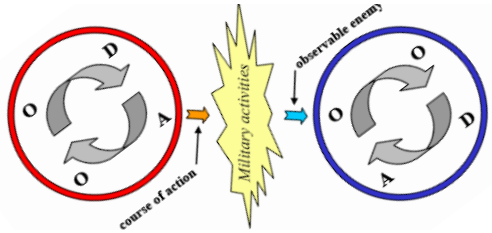
Strategy is the art of making use of time and space. I am less chary of the latter than the former. Space we can recover, time never. … I may lose a battle, but I shall never lose a minute. **Napoleon Bonaparte**

- Boyd's *O*bserve-*O*rient-*D*ecide-*A*ct Loop:



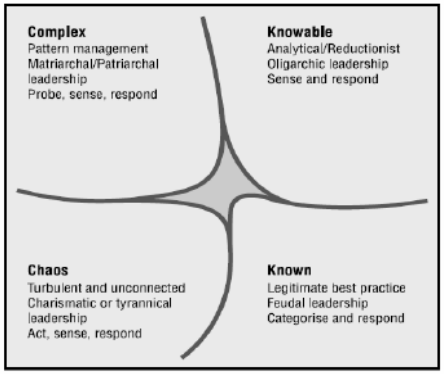
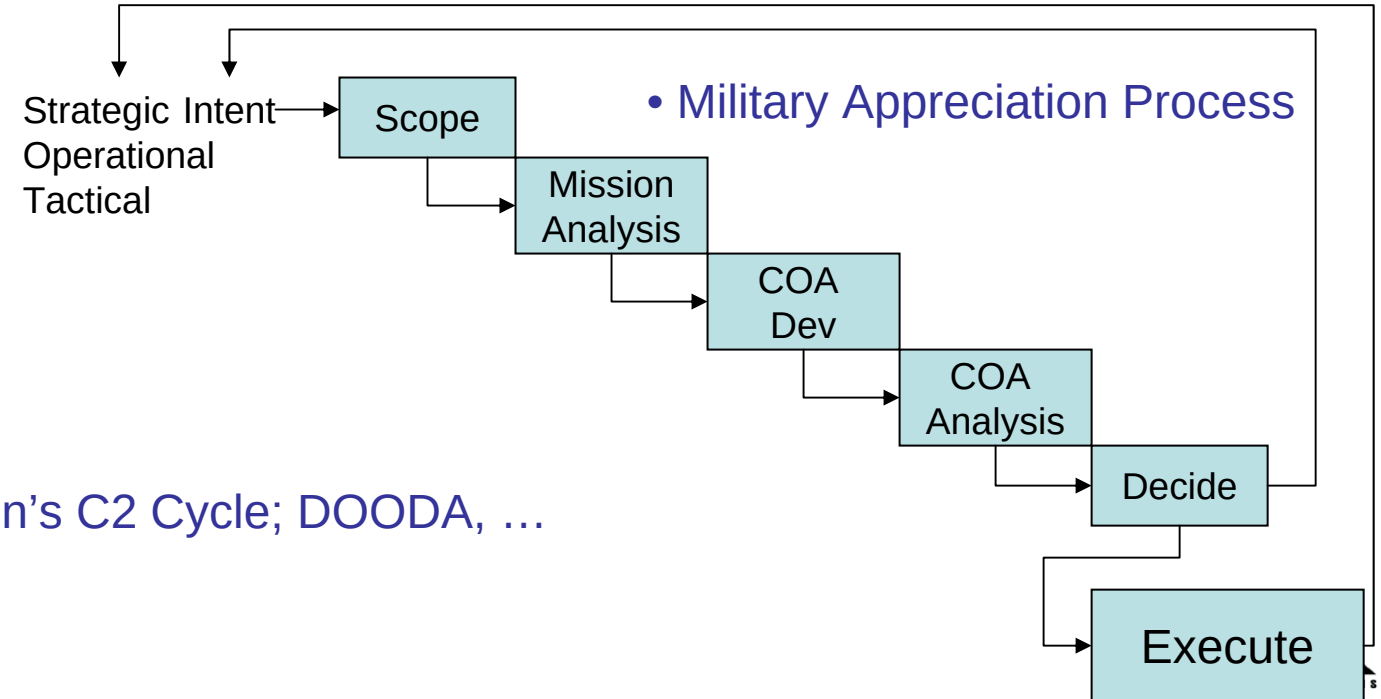


Figure 4: Cynefin Framework

- Snowden's Cynefin Framework: Different loops depending on *context*



- Military Appreciation Process

- *Elaborations:*

  Lawson's C2 Cycle; DOODA, …

Universality: Cycles and C2

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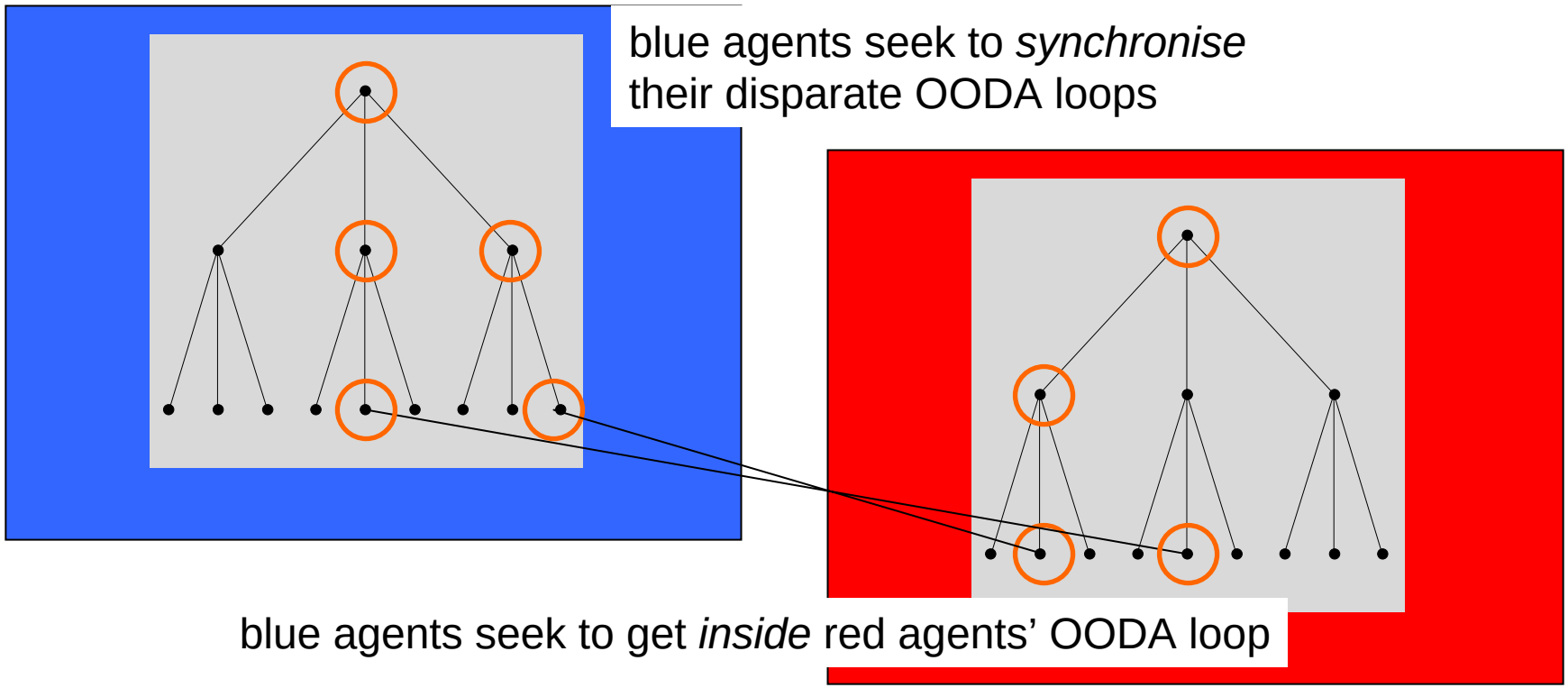
- *C2=cyclic dynamical process + structure (+fluctuations)*

every C2-node performs loop



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Kuramoto* Model

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1-D Oscillator:

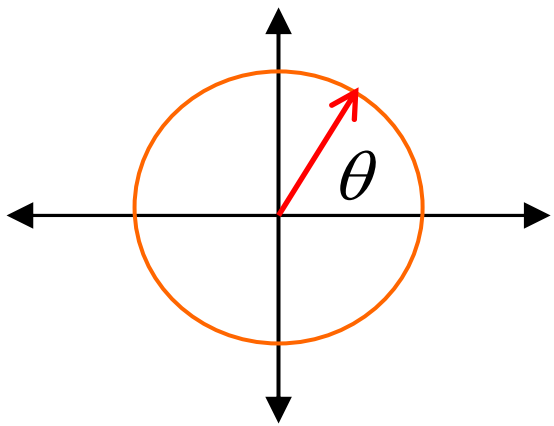
$$\chi_i(t) = e^{i\theta_i(t)}$$

$$\boxed{\dot{\theta}_i = \omega_i + \frac{K}{N}\sum_j A_{ij}\sin(\theta_j - \theta_i)}$$

natural frequency

coupling

network adjacency matrix



At critical coupling *self-synchronisation* occurs: two populations of oscillators *spontaneously* arise – **locked** and random **drifting**.
Kuramoto derived exact result for critical coupling, for *all-to-all infinite network* with frequencies randomly distributed according to symmetric unimodal density *g(ω)*:

$$K_c = 2/\pi g(0)$$

*Y. Kuramoto, Chemical Oscillations, Waves and Turbulence, Springer, Berlin, 1984;
S.H. Strogatz, *Physica* D 143 (2000) 1.

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Complex Networks

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Random networks develop *locked hubs* which unite as coupling increases.

Scale Free networks develop *one locked core* which increases as function of increasing coupling.

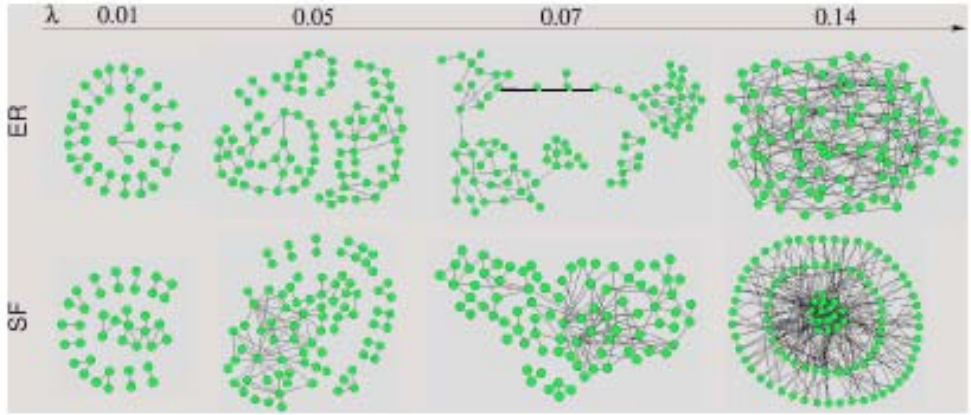

FIG. 34 Synchronization patterns of Erdős-Rényi (ER) and scale-free (SF) networks for several values of coupling λ (or J in our notations). From Gómez-Gardeñes *et al.* (2007).

Finite, general graph: lower bound for critical coupling (Jadbabaie, 2004):

$$K_L \geq 2\frac{\sqrt{N}\left\|\omega\right\|_2}{\lambda_2(L)}$$

Lowest nonzero eigenvalue of graph *Laplacian*

- *Key question: Interplay of frequency distribution, coupling and network characteristics enabling local and global locking.*
- *Key aim: design networks or assign functions in networks such that intended synchronisation is possible.*

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Mapping Kuramoto to Boyd

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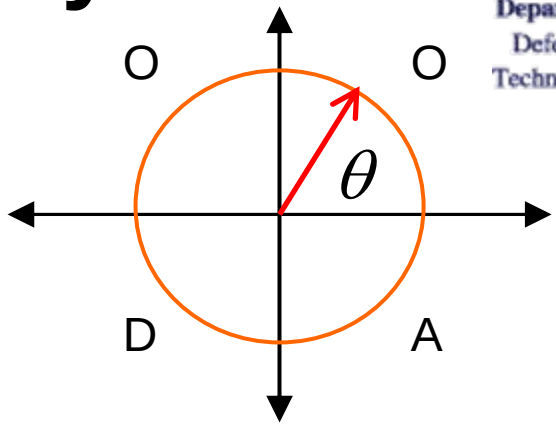

- θ = point of progress in decision cycle.
- *K* = Coupling = degree of tightness of control.
- ω = *natural* frequency of each node = inverse time period for processing appropriate information according to "environment" in order to advance through cycle.
- *A* = intra-C2 Network = not just communications connectivity, but also authority, collaborative, social, and visual networks.
  - *Who are my points of reference for my decision cycle?*
- Implicit assumption: complete transparency of OODA state of adjacent partners within a C2-system. *Not always realised*.
- Periodicity of *sine* response function: irrelevance of "stale" information or past decisions. Keep-to/out-pace adjacent partner's/enemies *current decision cycle*.

C2 Time Periods

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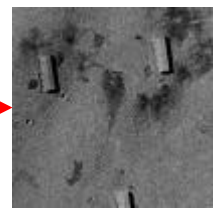
C2-level	Time Scales
Nat/Strat. National Security Committees	Long term acquisition; several days
Operational level	J5 – days-weeks J3 – hourly-daily
Government agencies; NGOs	days-weeks
Tactical-land – surface targets – theatre missiles	minutes-hours
Tactical-air combat	seconds - minutes



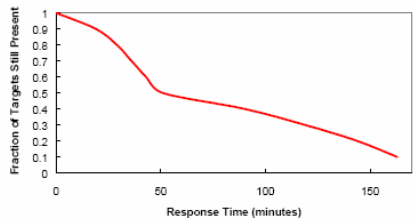


Figure 4. The fraction of targets still at the location where they were detected, as a function of response time

From Sullivan, 1999.

Complex Endeavours involve diversity of scales and networking of processes.

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When is locking/drifting good?

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- Nodes working in collaboration need to be able to lock with each other.
- Chief of Staff function (synchronising *products* not time) needs to drift to move from one function to another.
- Tactical node must exhibit hybrid behaviours:
  - lock inside enemy cycle at “Observe” and “Act”
  - lock with own force at “Orient” and “Decide”.

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Blue v Red C2 equations

cf Lanchester attrition and Hughes salvo equations

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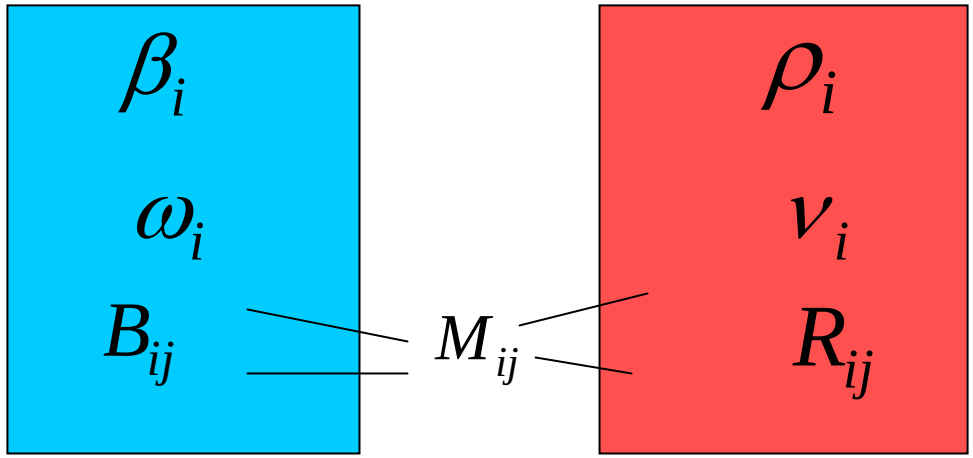
Phase angles

Intrinsic frequencies

Adjacency matrices



$$\dot{\beta}_i = \omega_i + \sigma_B \sum_{j=1}^{N_B} B_{ij} \sin(\beta_j - \beta_i) + \varsigma_B \sum_{j=1}^{N_{BR}} M_{ij} f(\rho_j - \beta_i)$$

$$\dot{\rho}_i = \nu_i + \sigma_B \sum_{j=1}^{N_B} R_{ij} \sin(\rho_j - \rho_i) + \varsigma_R \sum_{j=1}^{N_{BR}} M_{ij} f(\beta_j - \rho_i).$$

$$f(\rho_j(t) - \beta_i(t)) = \sin(\rho_j(t) + \lambda - \beta_i(t))\delta(\rho_j(t) - \kappa)$$

κ= point(s) at which blue can acquire knowledge of red's state
λ= point at which blue seeks to stay ahead of red's OODA loop.

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The questions

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- Can nodes lock/drift if their function is to lock/drift?
  - As a function of network structure?
  - As a function of coupling strength?
  - As a function of intrinsic frequency or distribution of frequencies?

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Conclusion

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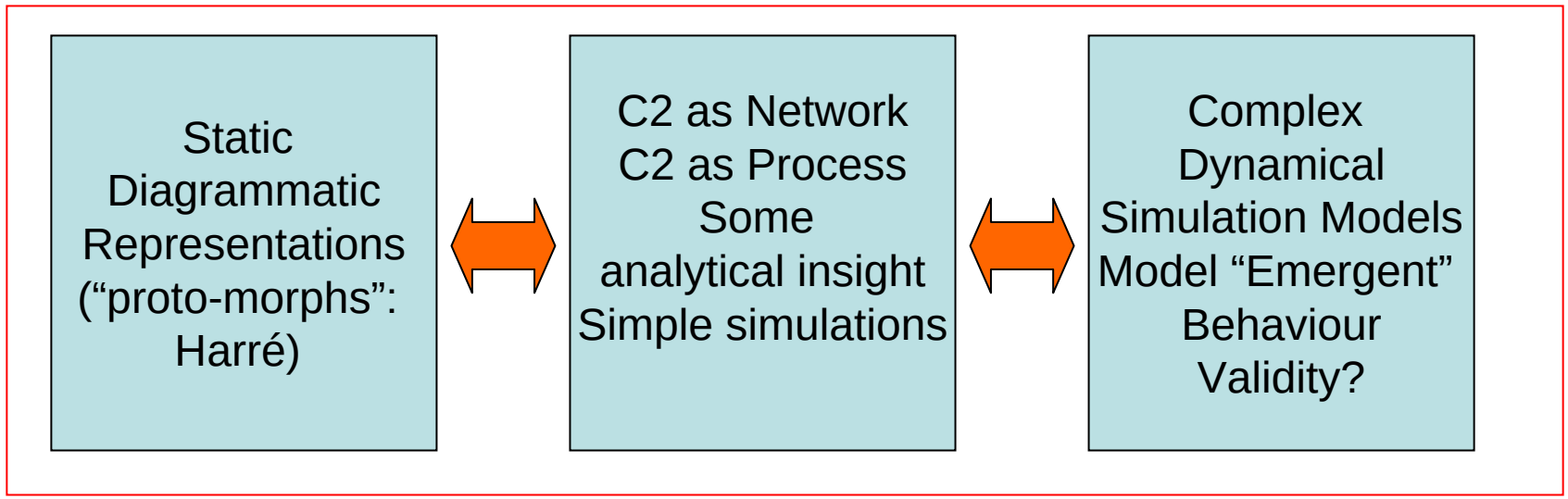
- Why is this a new paradigm?



Diversity/Spectrum of C2 Models: Enhanced Cross-Validation

- Analytical and simulation work, application to military case studies: *in progress*.

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