Australian Government
Department of Defence
Defence Science and Technology Group

Hybrid Human-Autonomous C2 systems: a modelling approach & adaptive control

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Overview

- 'C2' and models
- The model: network synchronisation
- Data, Model Tuning and Validation
- Introducing AI agents in a C2 system:
  - Smart Information Objects
  - Adaptive Control
- Conclusions

Command and Control (C2)

“C2 is the *system* empowering designated personnel to exercise lawful authority and direction over assigned forces.” (ADF doctrine)

“Command is the creative expression of human will necessary to accomplish the mission; control is the structures and process devised by command to enable it to *manage risk*. C2 is the establishment of common intent to achieve *coordinated action*.” (Pigeau-McCann)

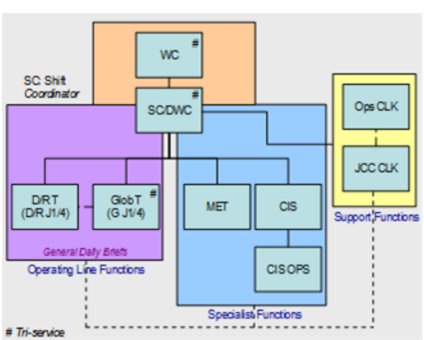
- Structure – Organisation
- Cognition
- Dynamics
- Distributed effort

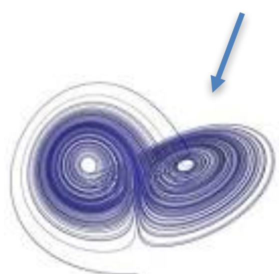
What is the gap for modelling C2?

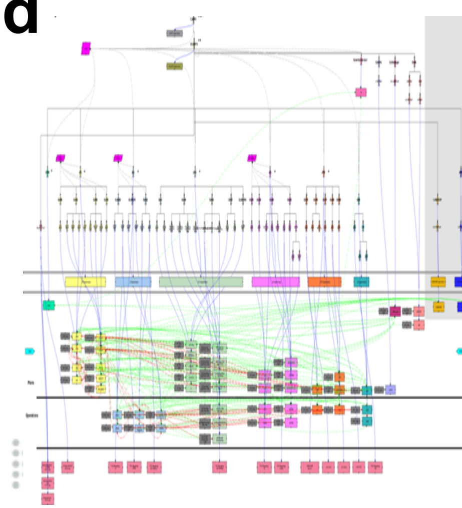
Proto-morphs[1]		Para-morphs[1]		Para-morphs[1]		Homeo-morphs[1]
OrgChart Network Workflow	⟷	Dynamical System	⟷	Computer Simulation Models eg Agent Distillation	⟷	Experiments War-games Exercises

1. R. Harré (1970) Taxonomy of Models

This is where many of the complexity metaphors are defined

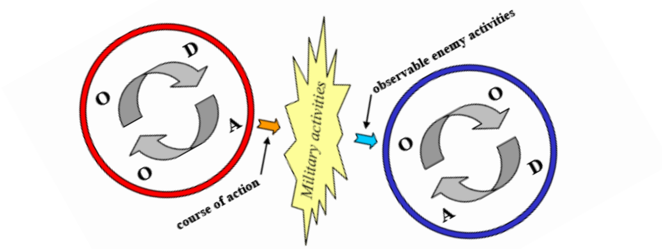




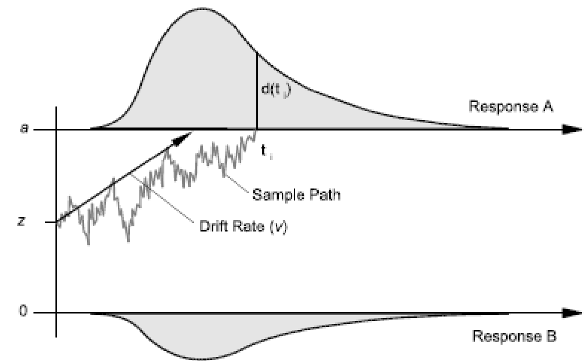


Models of cognition

Boyd 1987 – OODA Loop



Ratcliff 1978 – Diffusive Cognition



Endsley 1999 – 'SA'

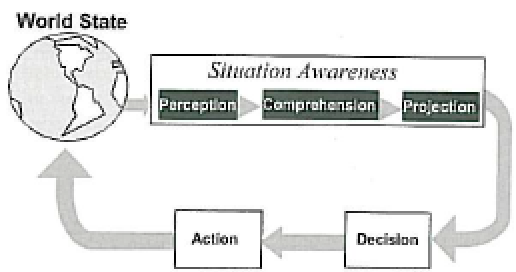
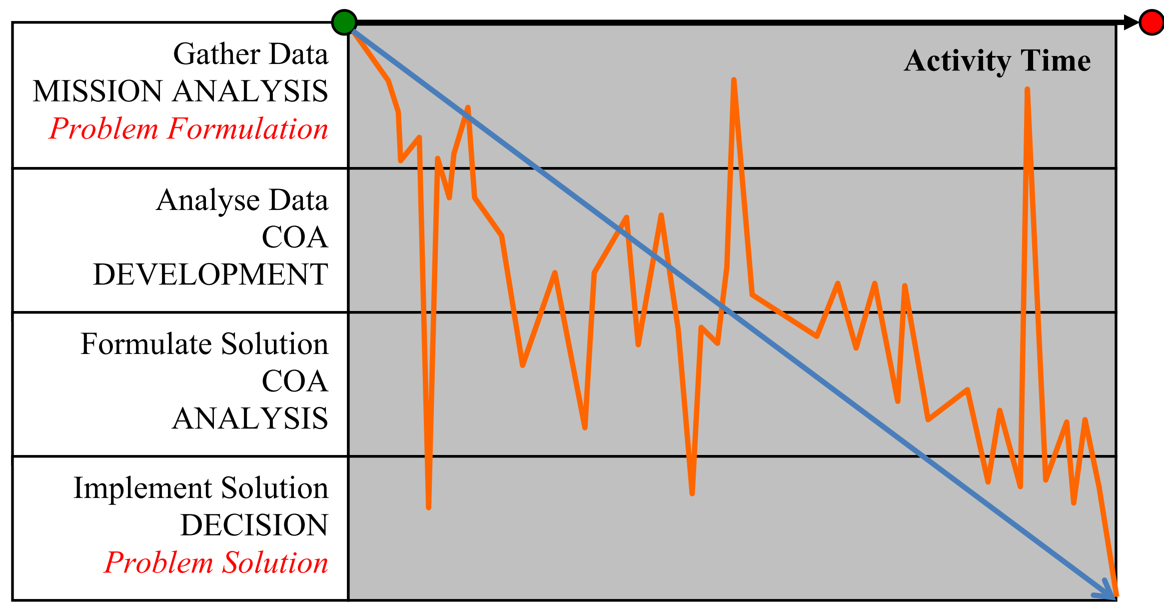
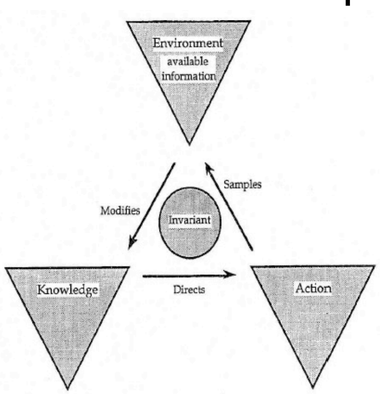


Figure 4.1. Situation awareness levels and the decision-action process.

Rittel & Webber 1973 Wicked problems + Lambert & Scholz 2005



Neisser 1976 – Perceptual Cycle



Distributed socio-technical systems

Stanton et al, 2006
Distributed **S**ituation **A**wareness

Social Network + Task network +
Information Network

Kalloniatis et al, ICCRTS 2016;
Applied Ergonomics, 2017
Situation **A**wareness **W**eighted **N**etwork

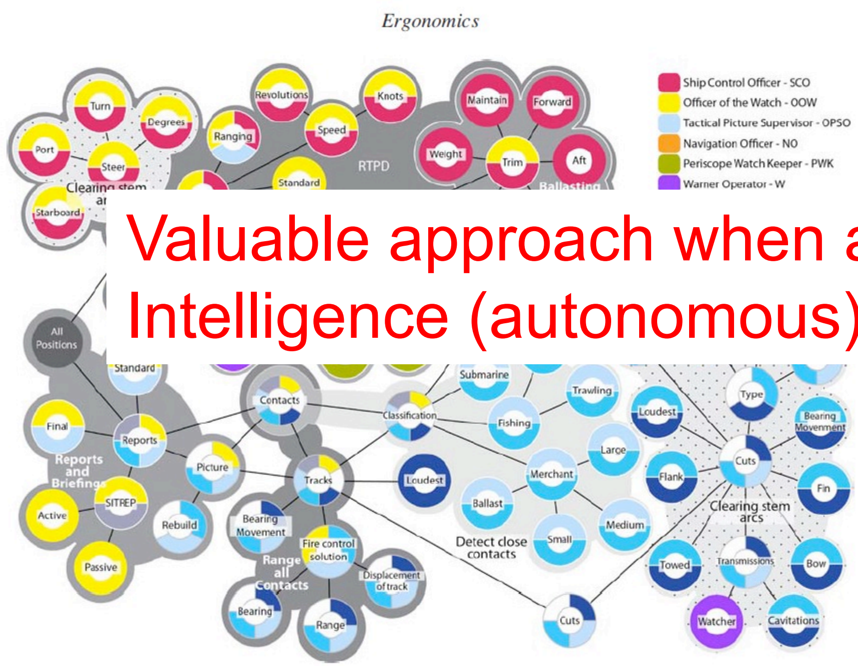
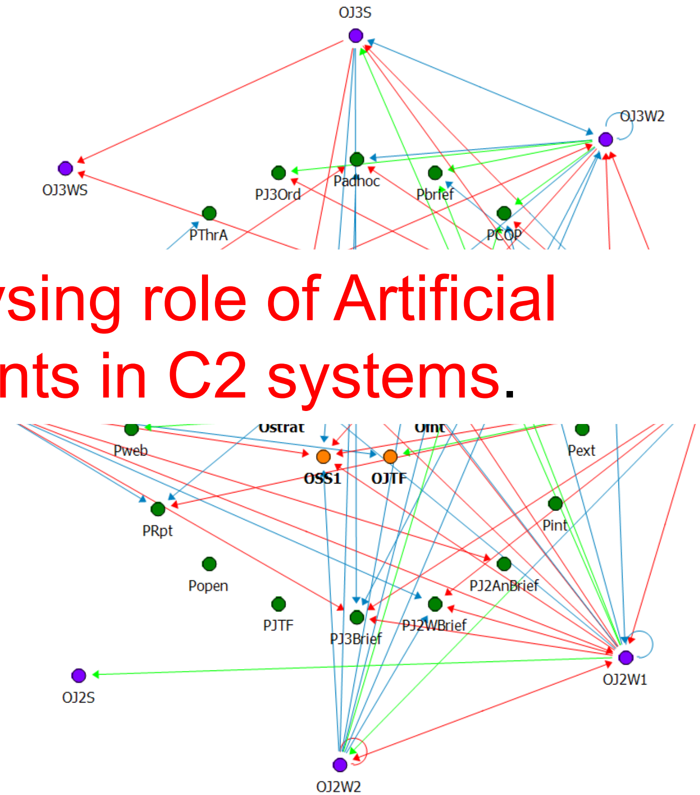


Figure 10. Integrated networks model.



Valuable approach when analysing role of Artificial Intelligence (autonomous) agents in C2 systems.

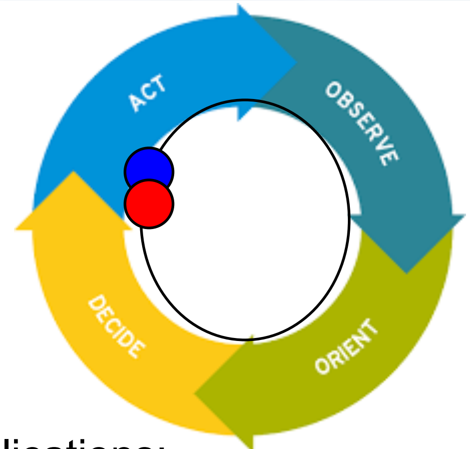
Eg how a submarine ops room brings vessel to periscope depth

Eg how SA flows in an ops watch during a crisis

A Mathematical Model (Kuramoto 1984)

$$\dot{\beta}_i = \omega_i + \sigma \sum_j A_{ij} \sin(\beta_j - \beta_i)$$

Coupling   Interactions

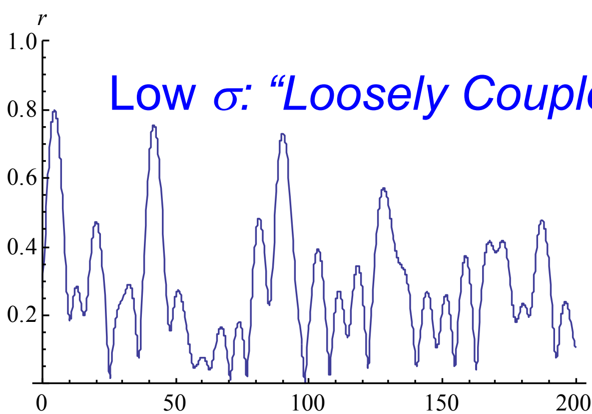


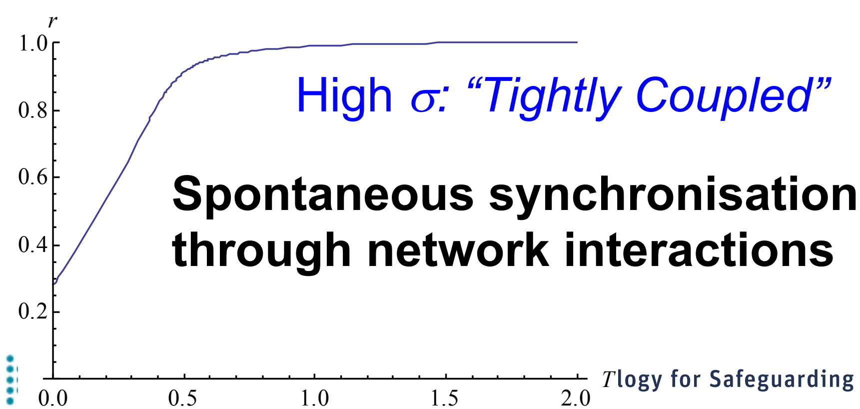
Socio/technical applications:

- Rhythmic applause (Neda et al 2000);
- Opinion dynamics (Pluchino et al 2006);
- Pedestrian crowds (Strogatz 2005);
- Decision making in animal groups (Leonard et al 2012);
- Planar vehicle coordination (Paley et al 2007);
- Control systems (Jadbabie et al 2004);
- Consensus protocol (Sarlette & Sepulchre 2009).

Measure of synchronisation:

$$r(t) = \frac{1}{N}\left|\sum_j e^{i\beta_j(t)}\right|$$



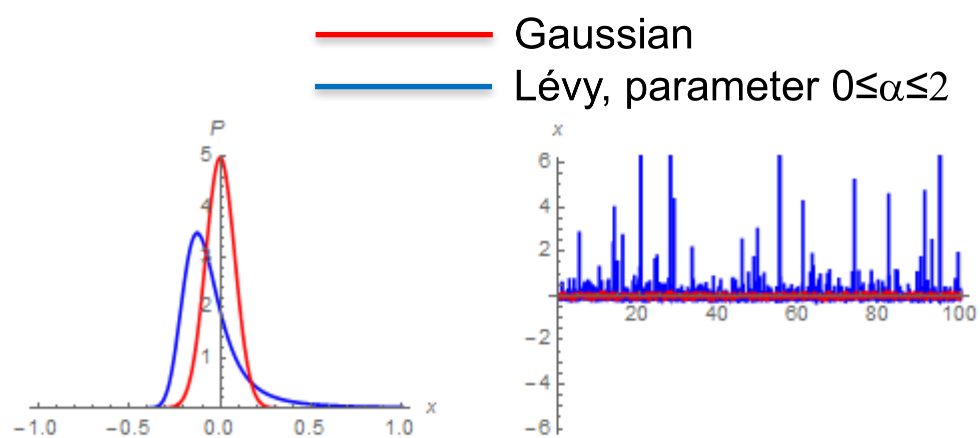


Stochastic Kuramoto model

$$\dot{\beta}_i(t) = \omega_i + \sigma \sum_j A_{ij} \sin(\beta_j(t) - \beta_i(t)) + L_i(t)$$

Typically uniform or normal (Gaussian) noise used.

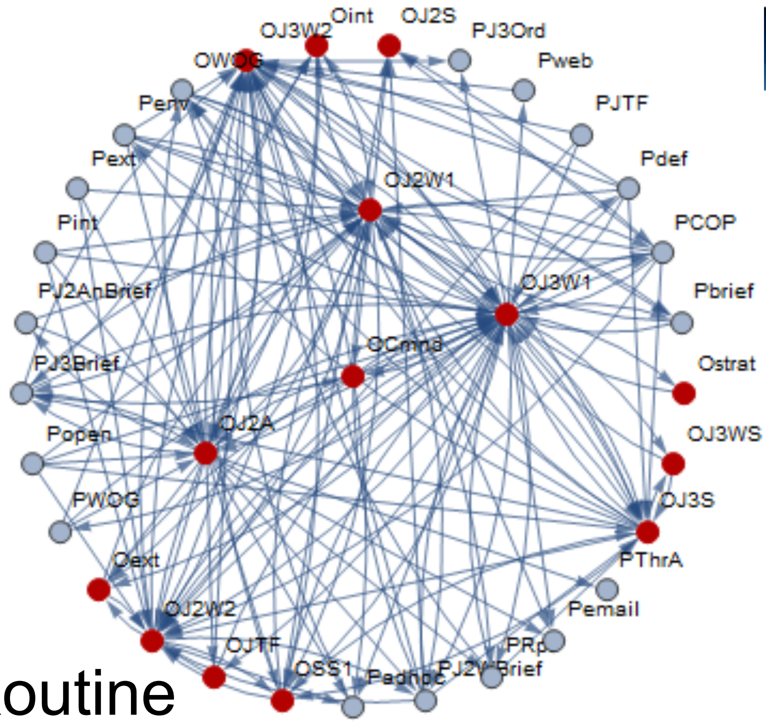
Let *L(t)* be given by Lévy noise (Kalloniatis & Roberts 2017)



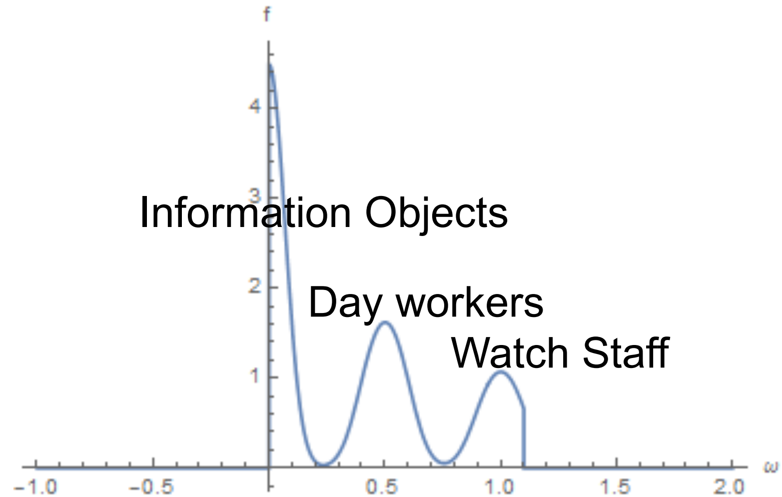
Validation Methods (Sargent 1984, Rykiel 1996)

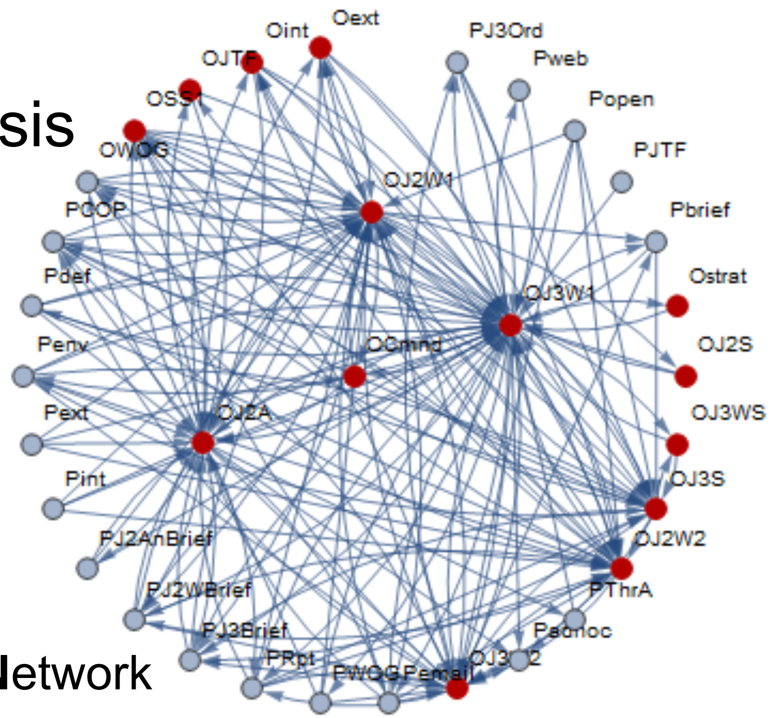
Type of Test	Description
Face Validity	SME asked if the model and its behaviour are reasonable
Turing Test	SME asked if they can discriminate between system and model output
Visualisation Techniques	Time series plots, state space phase plots form the basis for comparisons between system and model
Comparison to Other Models	The output of the model can be compared to other similar models
Event validity	A qualitative or quantitative comparison between model outputs and an actual event
Historical data validation	Using historical data to test if the model behaves as the system does
Extreme condition tests	The model output should be reasonable for any extreme and unlikely combination of values as compared to the system
Sensitivity analysis	This checks if the same parameters that cause the greatest effects on the model output are the ones to which the system is sensitive
Predictive validation	The model is used to forecast behaviour and then subsequently checks the system to see if the behaviour is replicated
Statistical validation	The statistical outputs of the model are the same as those of the system and the errors in the critical variables are within acceptable limits

Data



Routine





Crisis

People

Products

$$A_{ij} = \frac{1}{2}\left[A_{ij}^{(pull)} + A_{ij}^{(push)} \right]$$

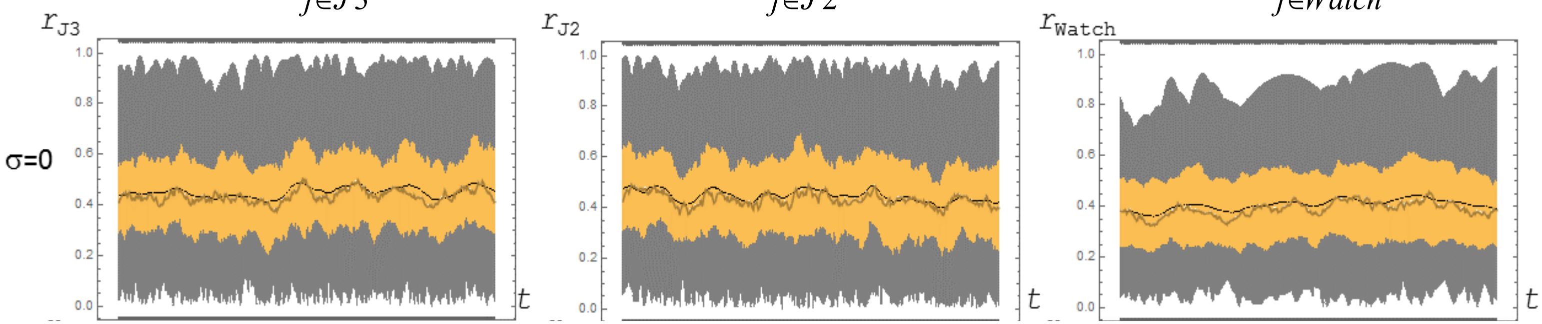
source

sink

Kalloniatis et al, ICCRTS 2014;
Applied Ergonomics, 2017
Situation **A**wareness **W**eighted **N**etwork

Tuning the model: steady-state=equilibrium

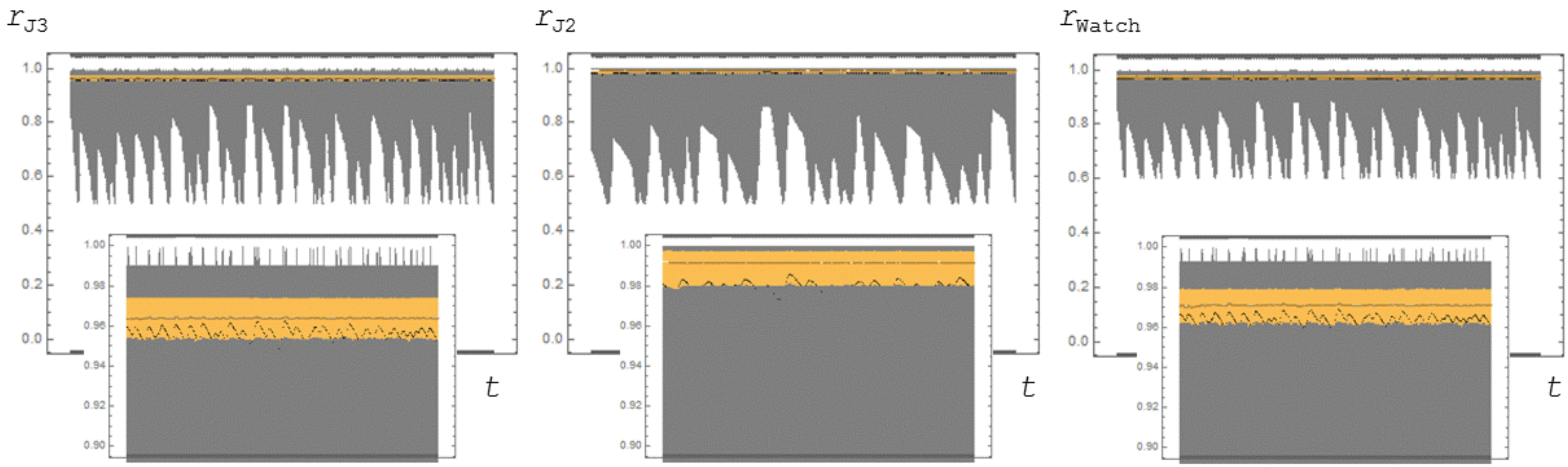
$$r_{J3}(t)=\frac{1}{4}\sum_{j\in J3}\left|e^{i\beta_j(t)}\right|,\quad r_{J2}(t)=\frac{1}{4}\sum_{j\in J2}\left|e^{i\beta_j(t)}\right|,\quad r_{Watch}(t)=\frac{1}{5}\sum_{j\in Watch}\left|e^{i\beta_j(t)}\right|.$$



Box-whisker charts:

100 runs at each time-step, same random seed for each parameter choice

Crisis scenario: σ=0.6, Lévy noise α=1.4, network 2



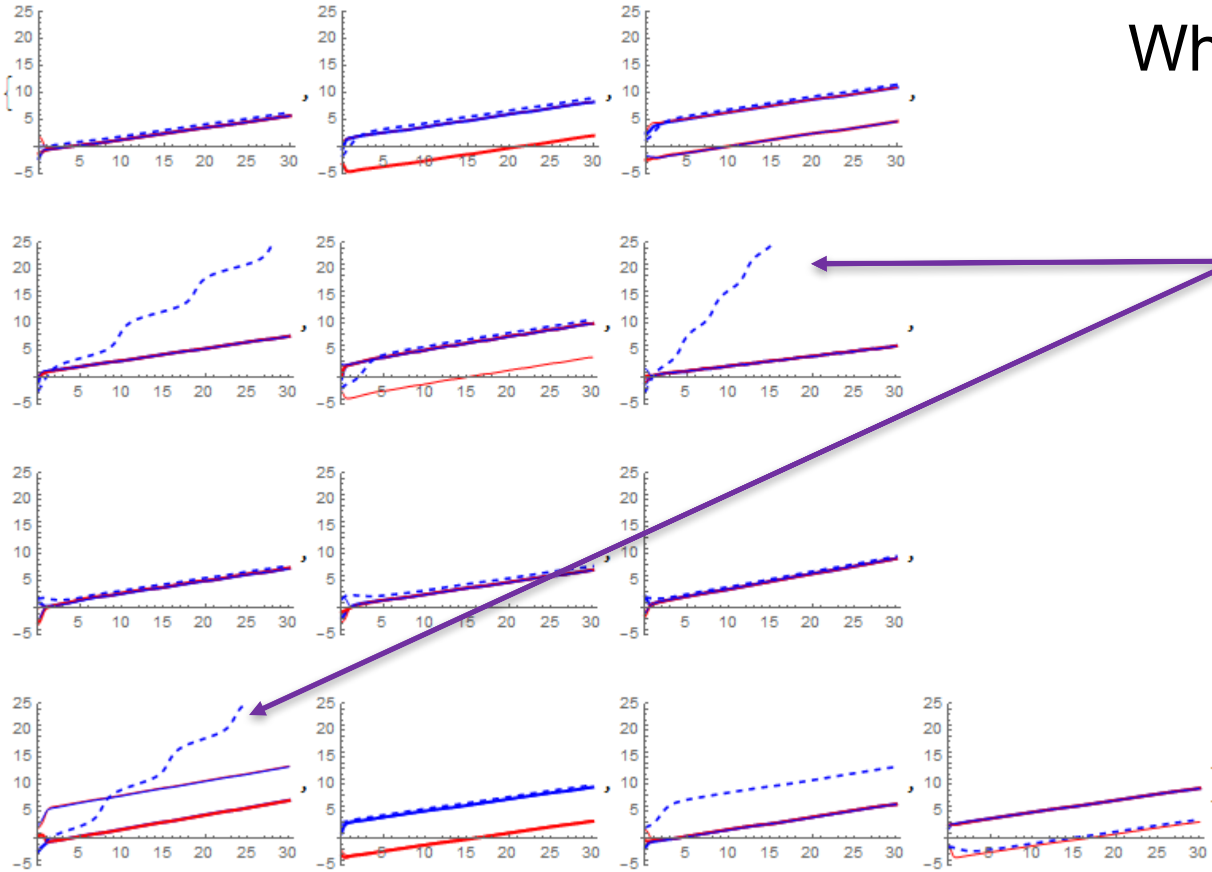
At coupling providing equilibrium for routine operations, crisis network leads to loss of synchrony with Pr=13%

– consequence of higher centralisation of network.

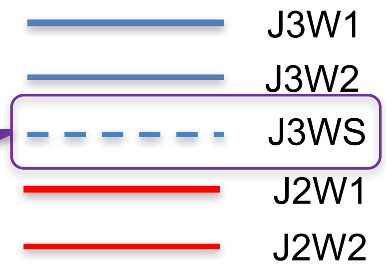
Contingency Theory: ‘network centric’ better in crises!

V A L I D A T I O N (crude but such is the data)

Disentangling cause-and-effect



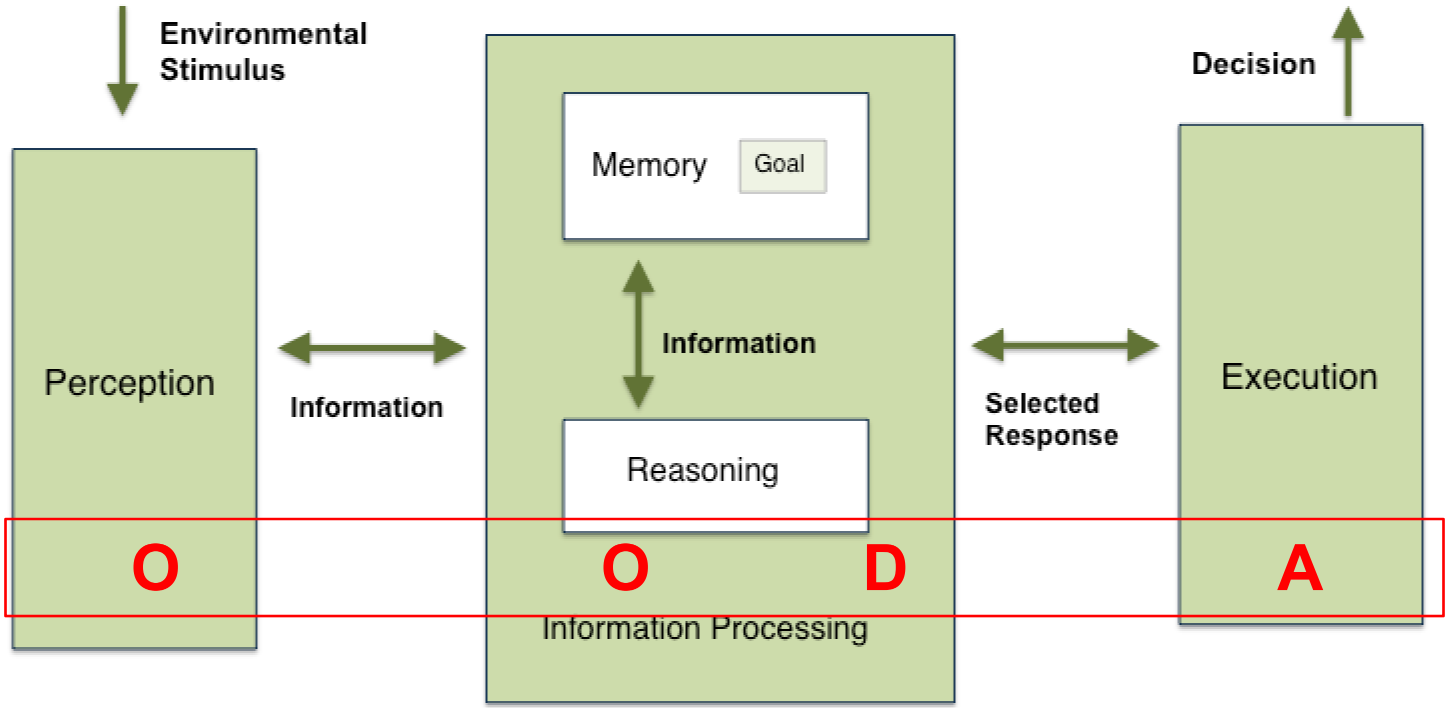
Who's to 'blame'?



J3WS: deg=2, Most poorly connected member of the 'crew'

Instances of "failed synchronisation"

Cognitive architecture for 'HyCCo*' AI agents



*Hybrid Cognitive Collaborative

Hieb, 21st ICCRTS, 2016

On AI, Autonomy and OODA

From Proud, Hart, Mrozinski 2003,
Method for Determining Level of Autonomy to Design into Human Spaceflight Vehicle

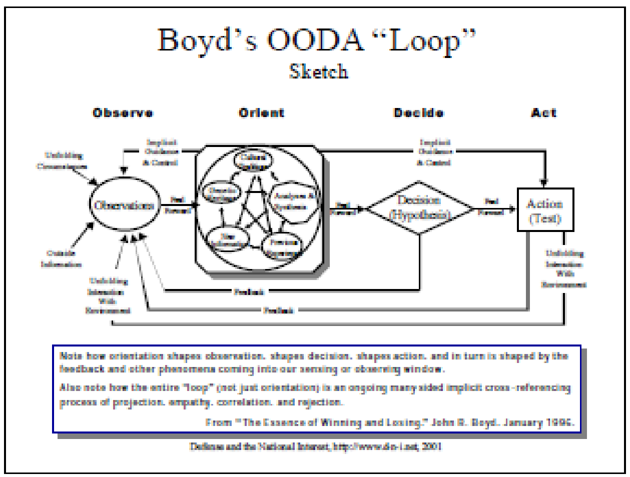
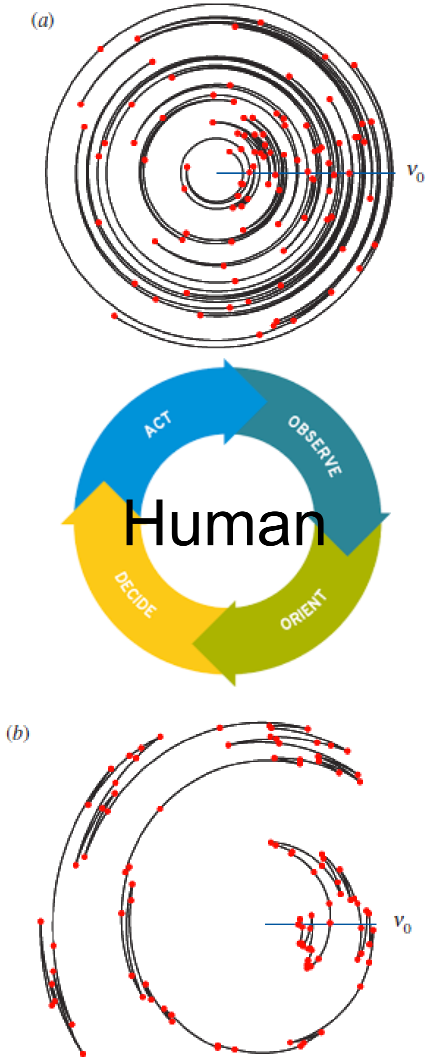


Figure 1. Boyd's OODA Loop [1]

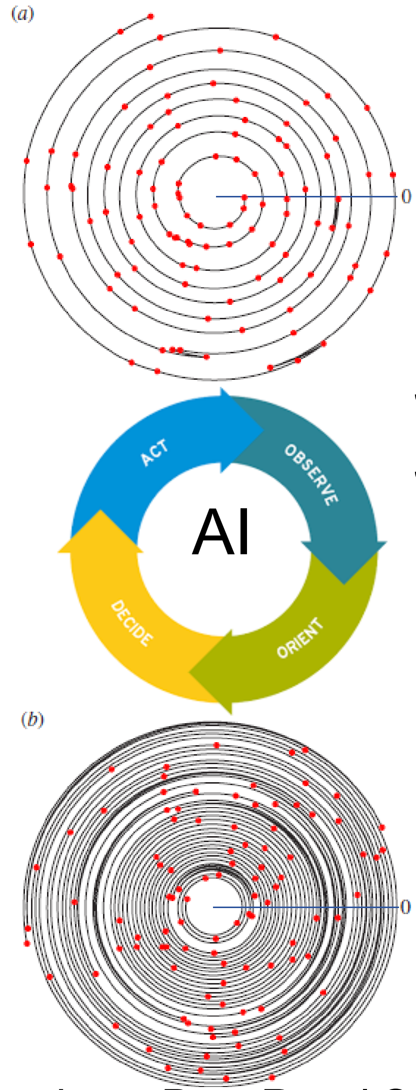
Level	Observe	Orient	Decide	Act
8	The computer gathers, filters, and prioritizes data without displaying any information to the human.	The computer predicts, interprets, and integrates data into a result which is not displayed to the human.	The computer performs ranking tasks. The computer performs final ranking, but does not display results to the human.	Computer executes automatically and does not allow any human interaction.
7	The computer gathers, filters, and prioritizes data without displaying any information to the human. Though, a "program functioning" flag is displayed.	The computer anlayzes, predicts, interprets, and integrates data into a result which is only displayed to the human if result fits programmed context (context dependant summaries).	The computer performs ranking tasks. The computer performs final ranking and displays a reduced set of ranked options without displaying "why" decisions were made to the human.	Computer executes automatically and only informs the human if required by context. It allows for override ability after execution. Human is shadow for contingencies.
6	The computer gathers, filters, and prioritizes information displayed to the human.	The computer overlays predictions with analysis and interprets the data. The human is shown all results.	The computer performs ranking tasks and displays a reduced set of ranked options while displaying "why" decisions were made to the human.	Computer executes automatically, informs the human, and allows for override ability after execution. Human is shadow for contingencies.
5	The computer is responsible for gathering the information for the human, but it only displays non-prioritized, filtered information.	The computer overlays predictions with analysis and interprets the data. The human shadows the interpretation for contingencies.	The computer performs ranking tasks. All results, including "why" decisions were made, are displayed to the human.	Computer allows the human a context-dependant restricted time to veto before execution. Human shadows for contingencies.
4	The computer is responsible for gathering the information for the human and for displaying all information, but it highlights the non-prioritized, relevant information for the user.	The computer analyzes the data and makes predictions, though the human is responsible for interpretation of the data.	Both human and computer perform ranking tasks, the results from the computer are considered prime.	Computer allows the human a pre-programmed restricted time to veto before execution. Human shadows for contingencies.
3	The computer is responsible for gathering and displaying unfiltered, unprioritized information for the human. The human still is the prime monitor for all information.	Computer is the prime source of analysis and predictions, with human shadow for contingencies. The human is responsible for interpretation of the data.	Both human and computer perform ranking tasks, the results from the human are considered prime.	Computer executes decision after human approval. Human shadows for contingencies.
2	Human is the prime source for gathering and monitoring all data, with computer shadow for emergencies.	Human is the prime source of analysis and predictions, with computer shadow for contingencies. The human is responsible for interpretation of the data.	The human performs all ranking tasks, but the computer can be used as a tool for assistance.	Human is the prime source of execution, with computer shadow for contingencies.
1	Human is the only source for gathering and monitoring (defined as filtering, prioritizing and understanding) all data.	Human is responsible for analyzing all data, making predictions, and interpretation of the data.	The computer does not assist in or perform ranking tasks. Human must do it all.	Human alone can execute decision.

Table 2. Level of Autonomy Assessment Scale

Assumption: difference between human and AI



Slow-
Sticky-
Jumpy



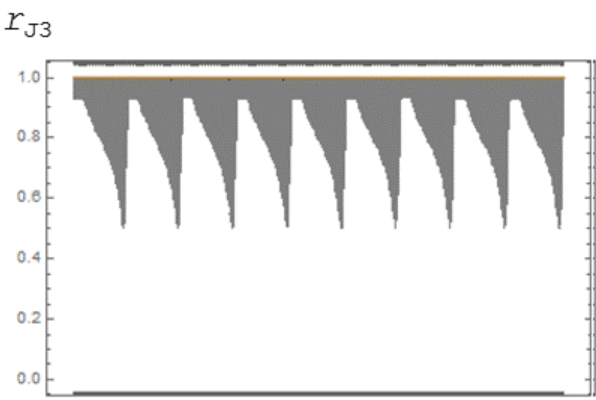
Fast-
Sticky-
Smooth

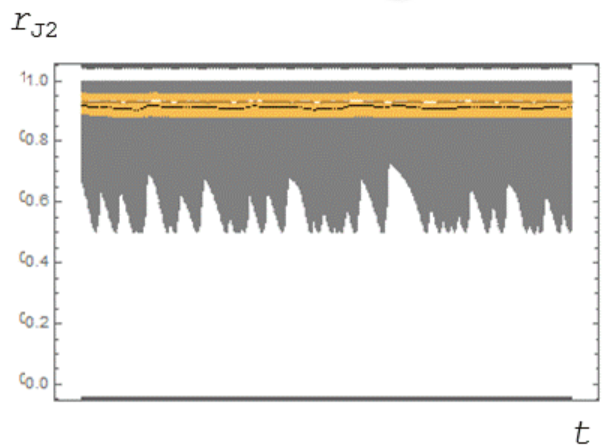
‘Wrapped pdf’s’ for jump processes from Yeh, Harris, Jupp, Proc.Royal.Soc.A, 2013

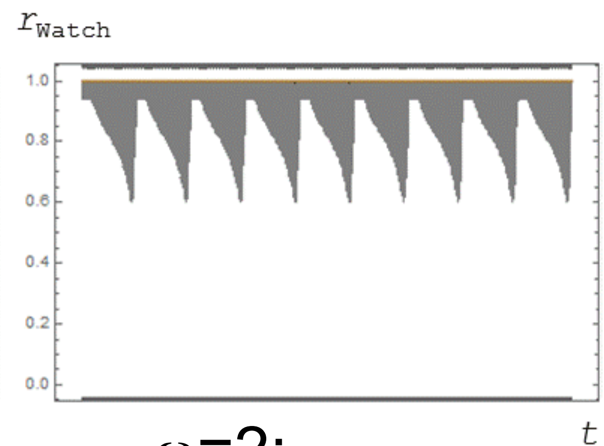
Interventions I: ‘smart’ Information Objects

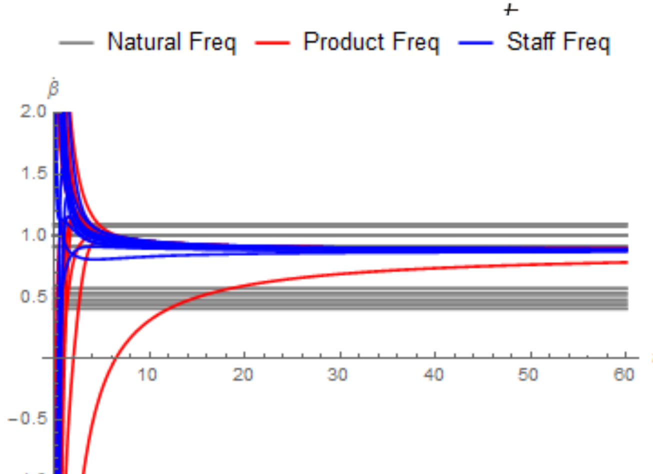
Kalloniatis, ICCRTS 2016

ω=1



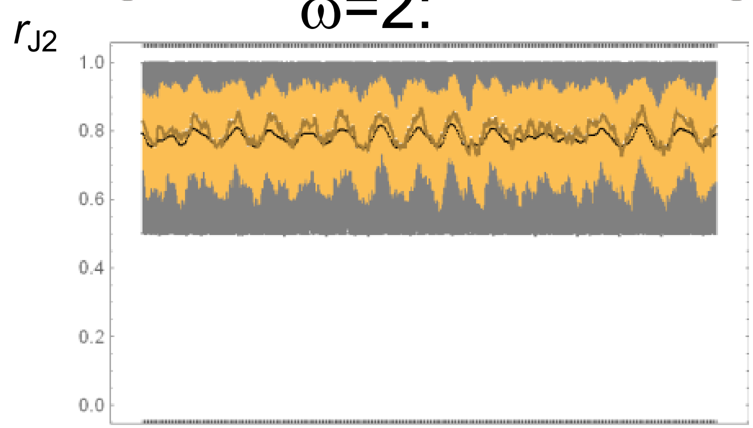




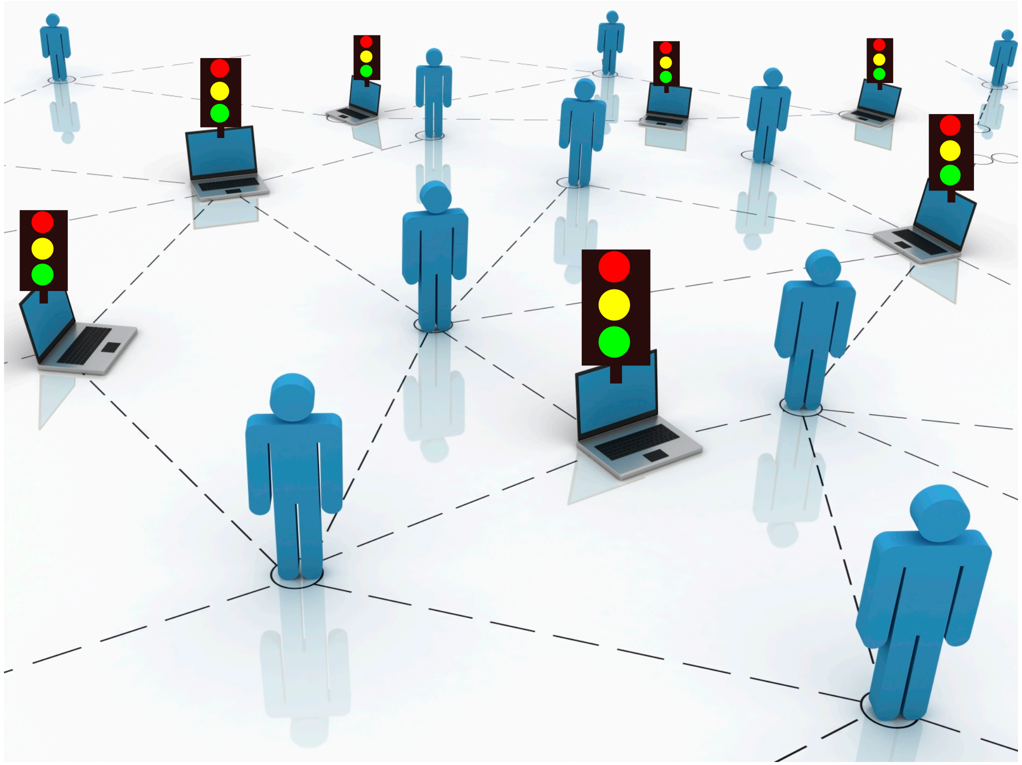


But not too fast …

ω=2:



Interventions III: Adaptive lags



Control by Adaptive lags

$$\dot{\beta}_i(t) = \omega_i + \sigma \sum_{j=1}^{N} A_{ij} \sin(\beta_j(t) - \beta_i(t) + \varphi_i(t))$$

$$\dot{\varphi}_i(t) = \tau b_i \sin(\Omega t - \beta_i(t))$$

Ω = external driving frequency,
b_i = (1,0) – select driven phases, or
ρ = density of driven phases=Nc/N

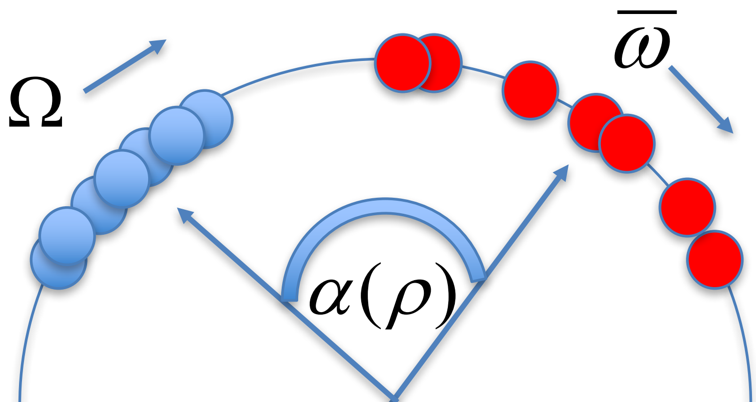
For range of (τ,ρ,Ω) enables *perfect synchronisation* of majority of phases at frequencies $\Omega > \overline{\omega}$.
(Brede & Kalloniatis, 2017)

Which agents should be driven?

- Staff?
- Information Objects?
- Both?
- Subsets?

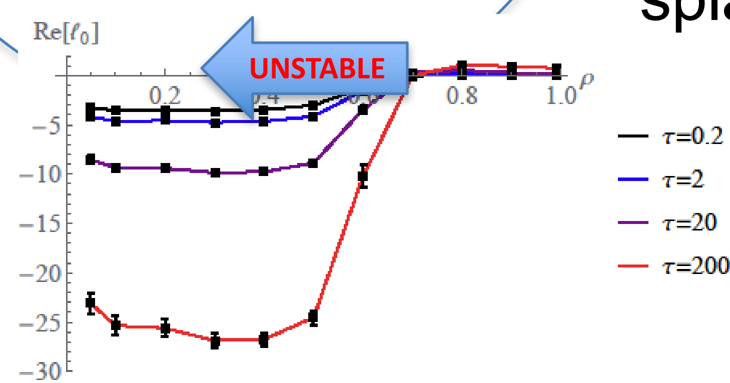
Origin of effect – eg random regular graphs

- Uncontrolled
- Controlled

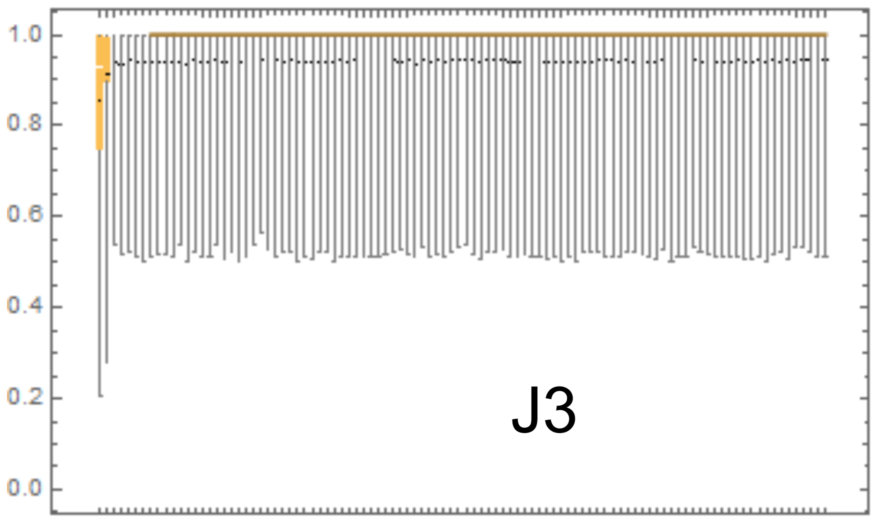


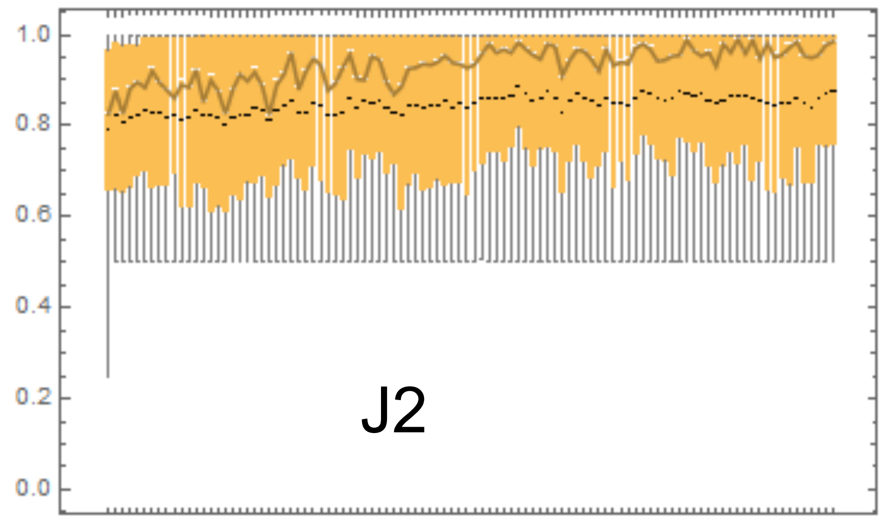
Adaptive lags allow micro-mutual adjustment giving minimal splay and synch to driving freq.

When α is too large Lyapunov instability follows:

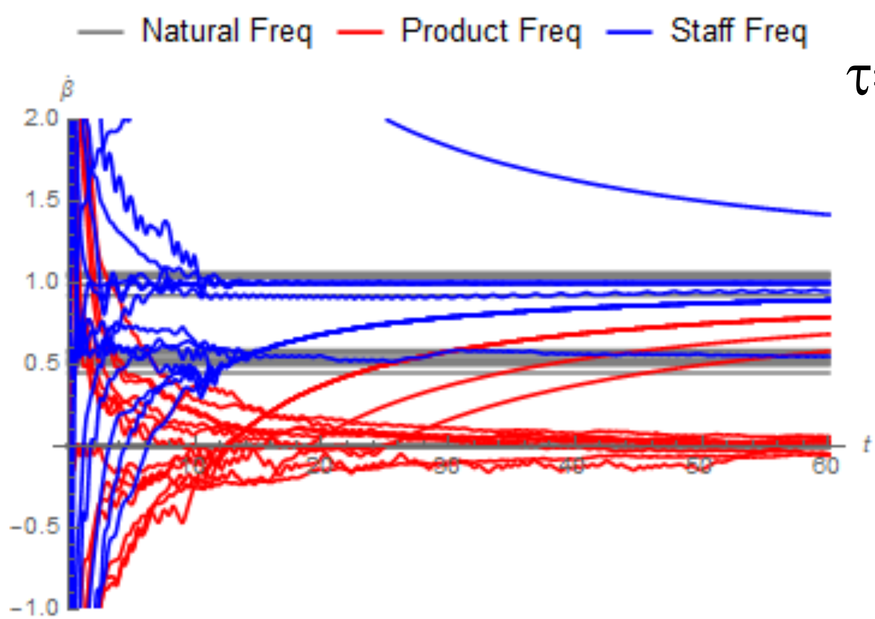


Uncontrolled self-synch to *mean freq* through ordinary Kuramoto mechanism with large 'splay'.



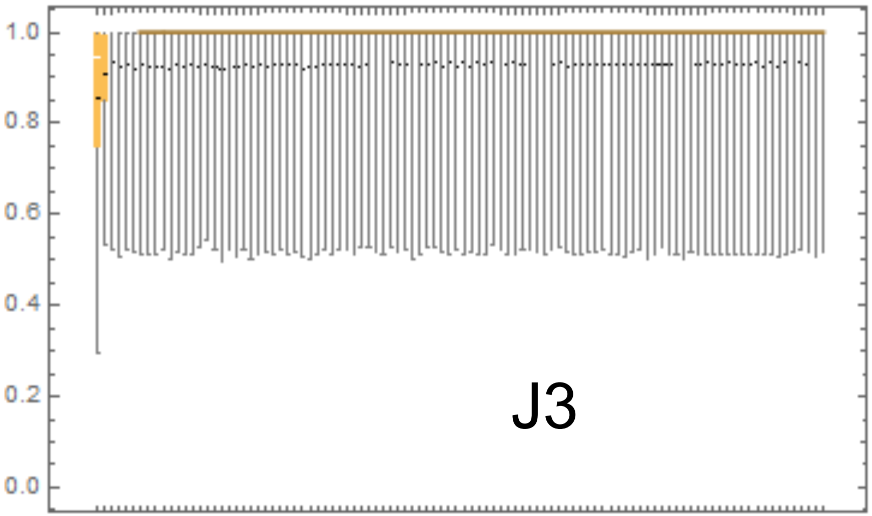


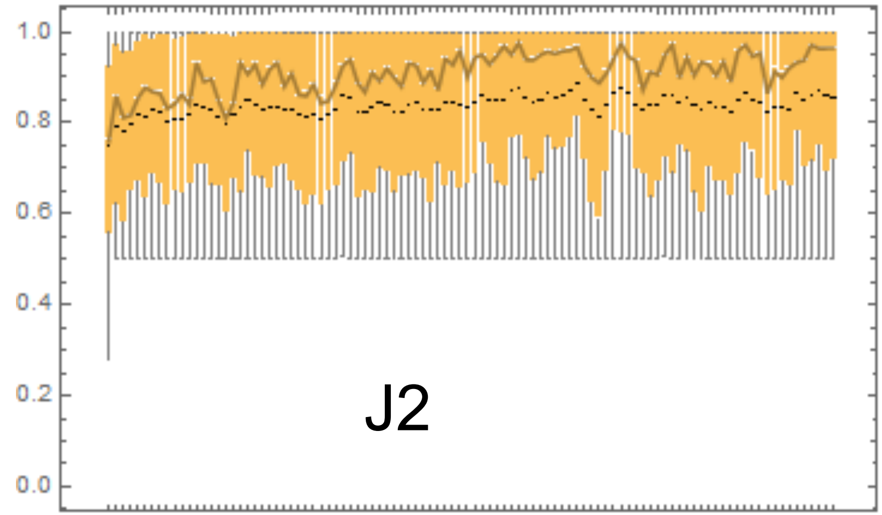
ρ=1



τ=10, Ω=1

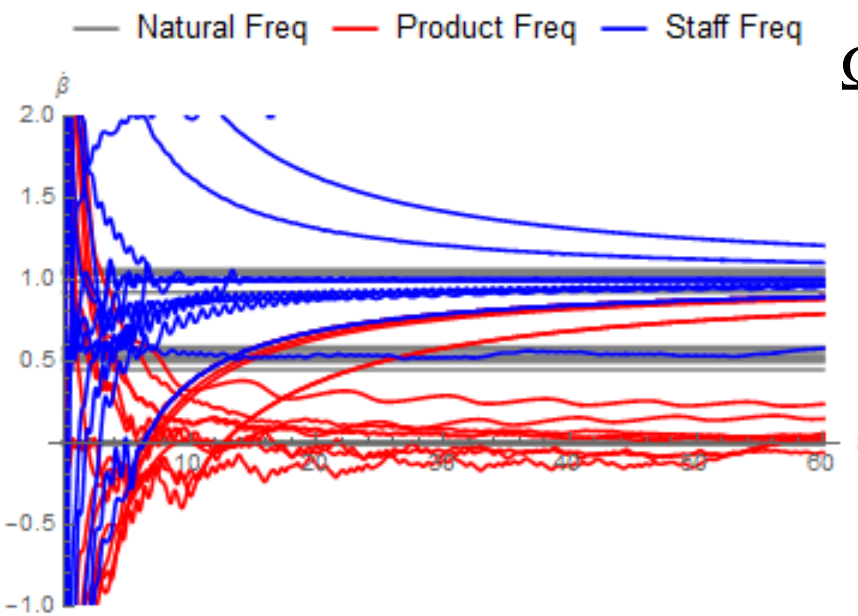
Disconnect btw people and information

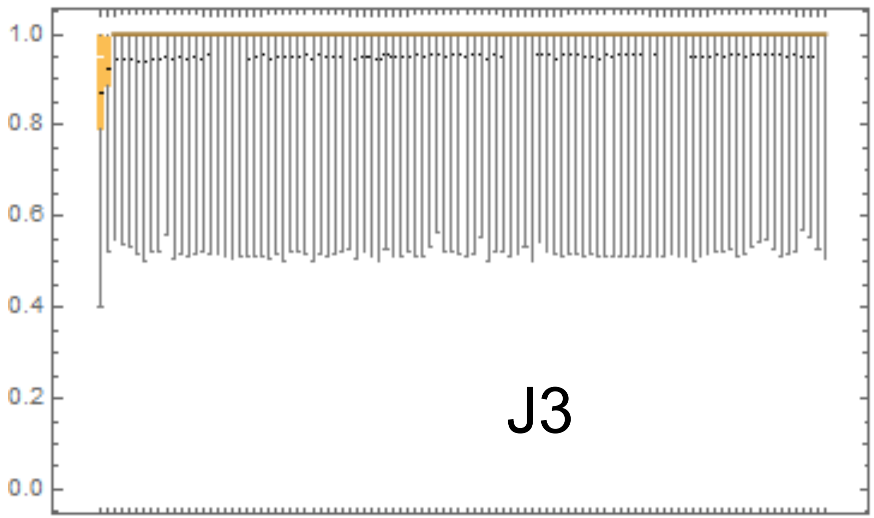


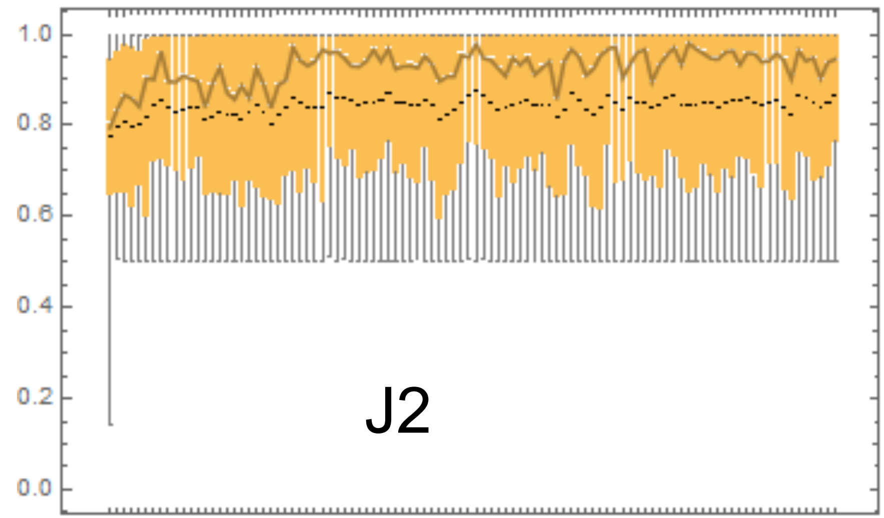


ρ=0.9

Ω=1

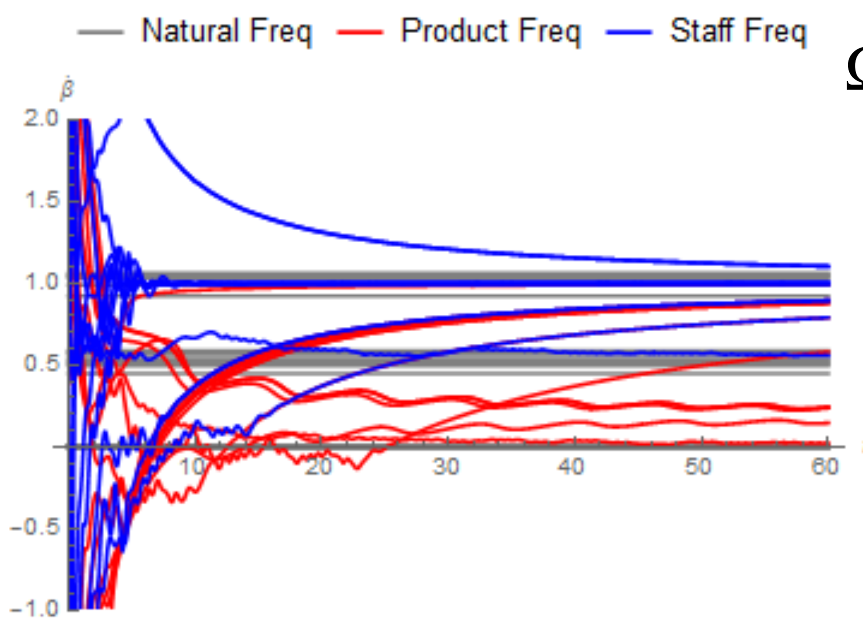


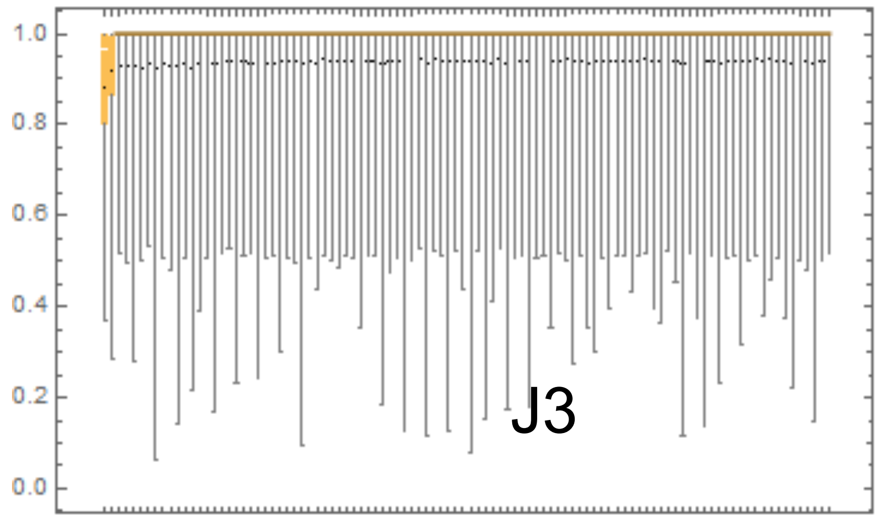


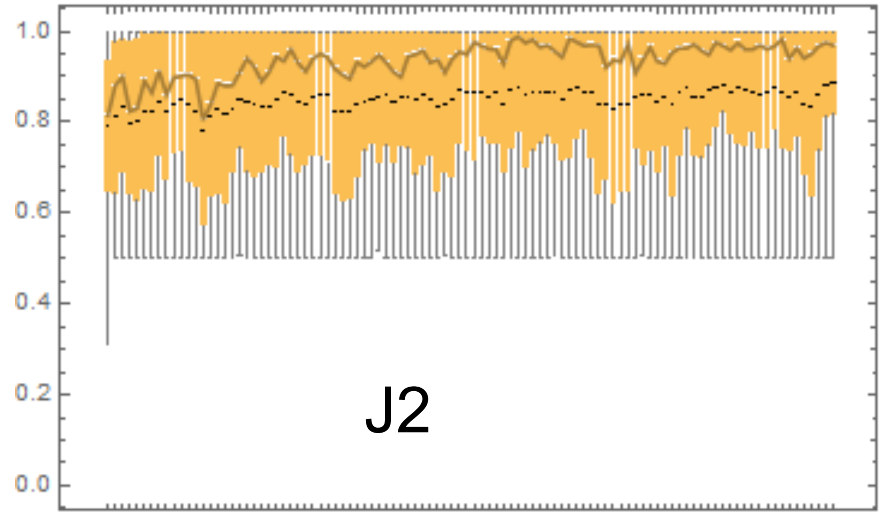


$\rho=0.6$

$\Omega=1$

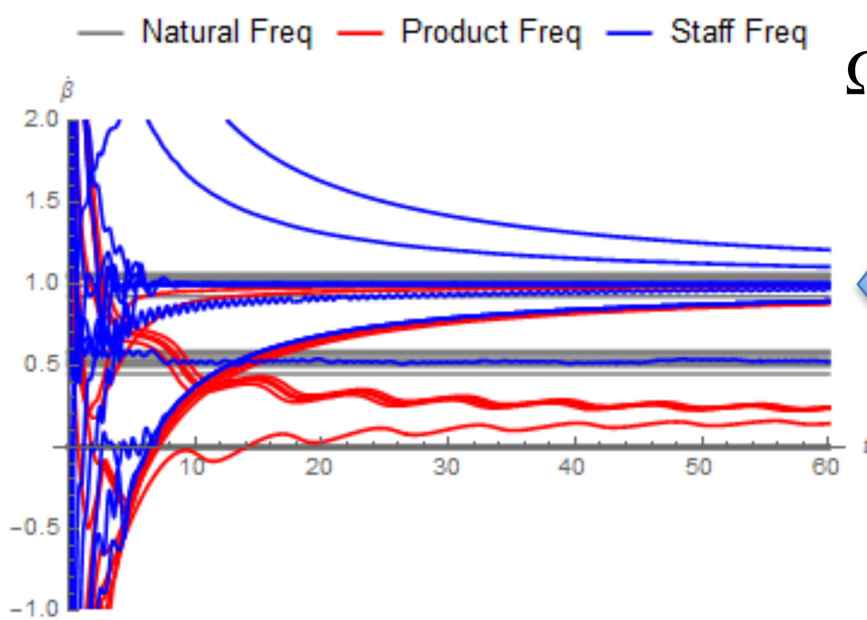




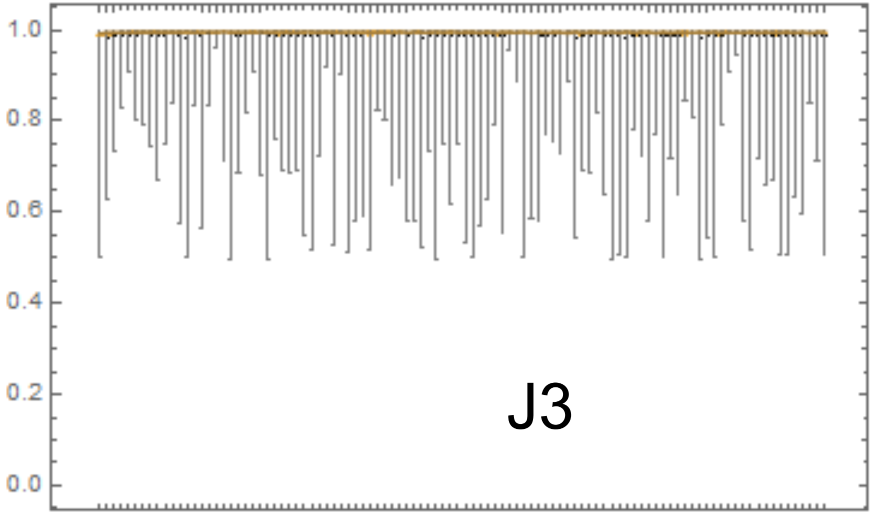


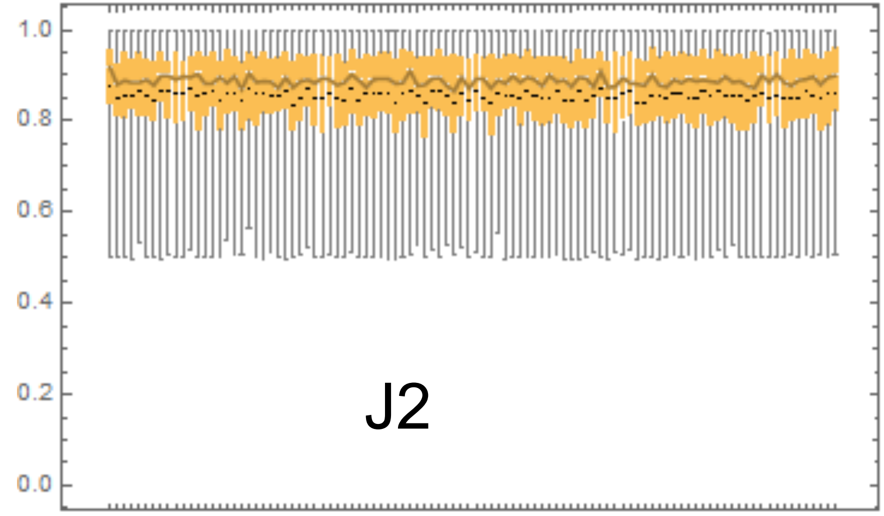
ρ=0.45

Ω=1

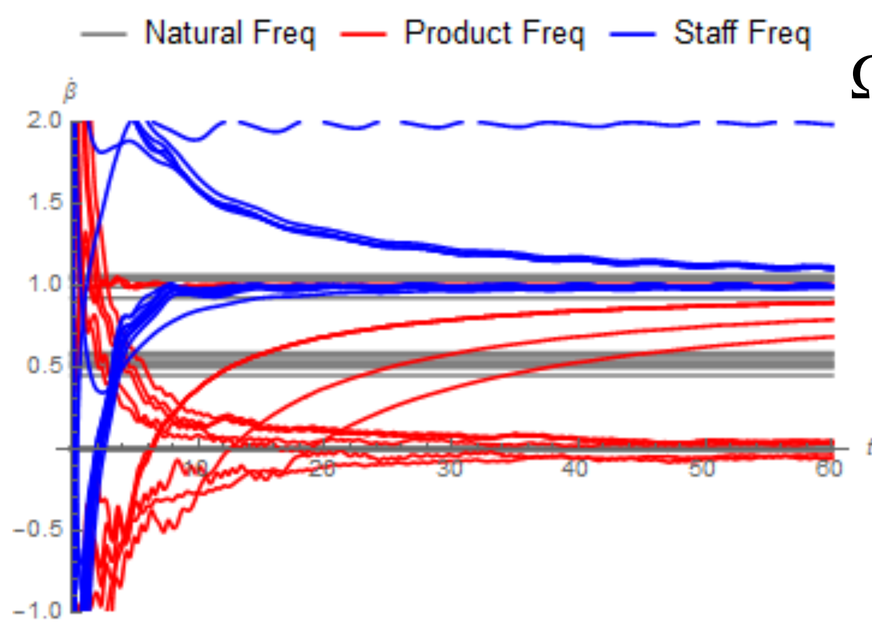


Good!
People at optimal freq, some information synched.



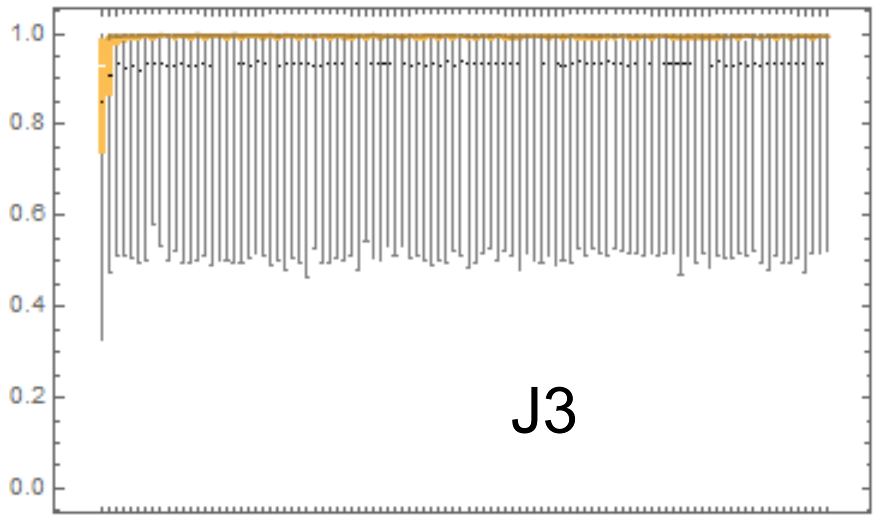


IO only

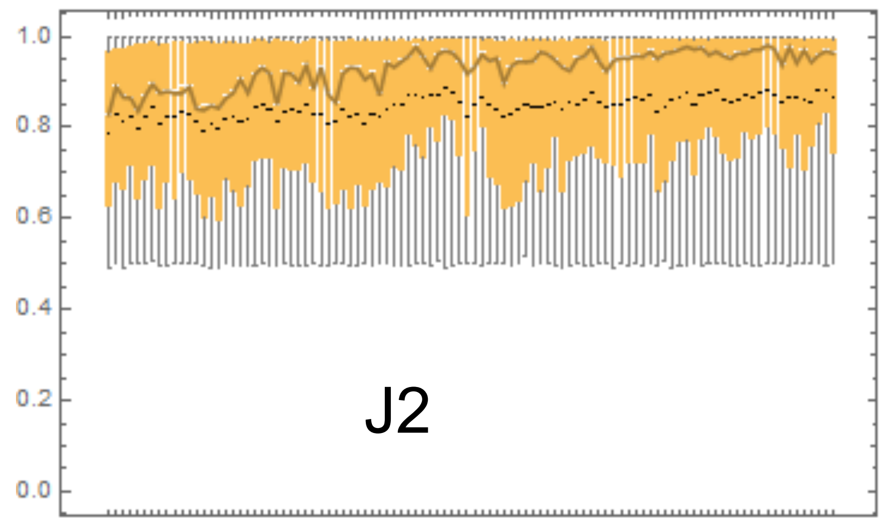


Ω=1

Not as good.



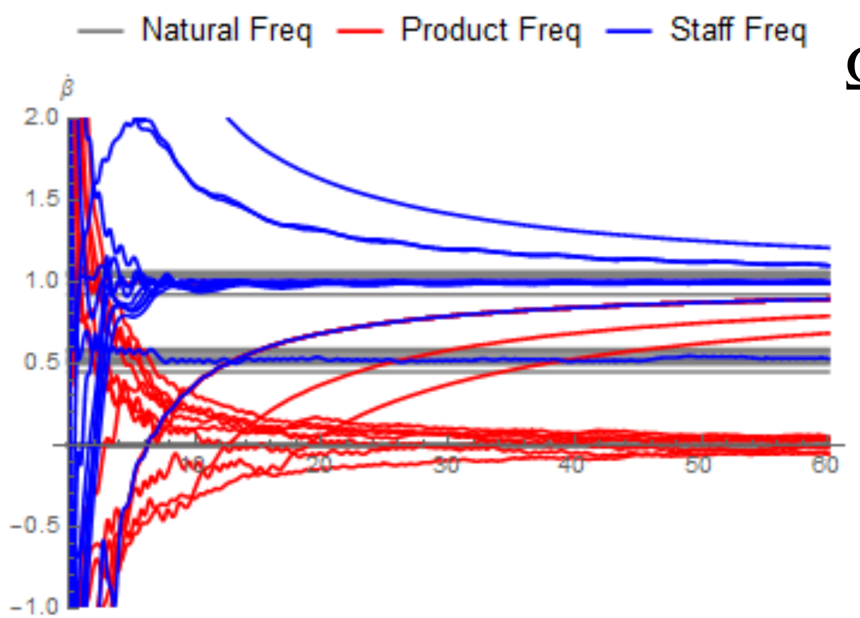
1.0
0.8
0.6
0.4
0.2
0.0
J3



1.0
0.8
0.6
0.4
0.2
0.0
J2

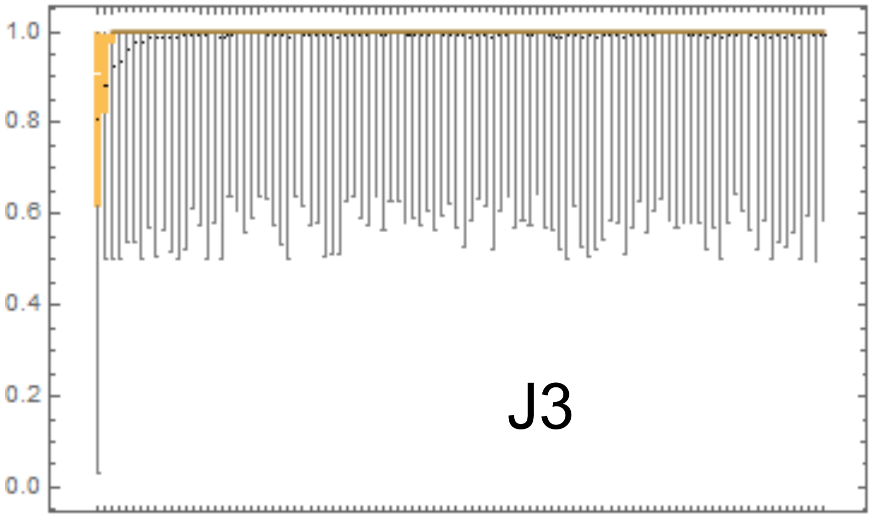
Ω=1

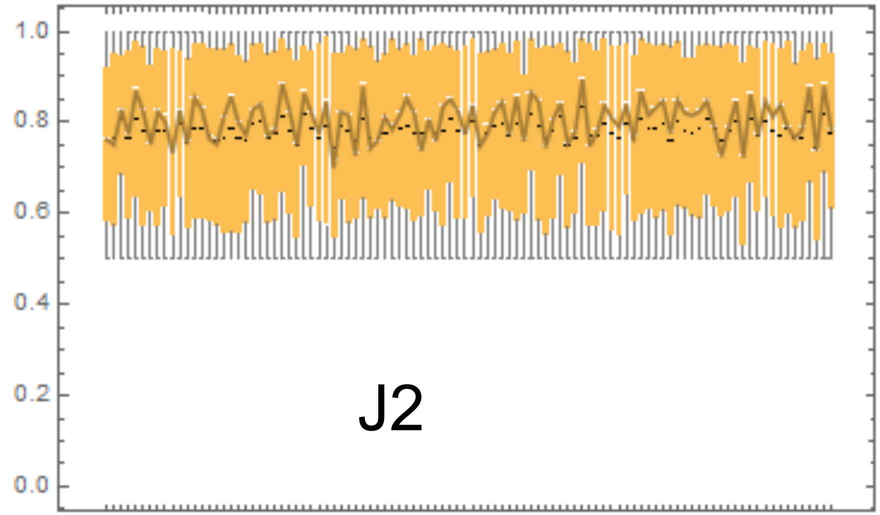
IO+
ρ=0.8



Natural Freq
Product Freq
Staff Freq
2.0
1.5
1.0
0.5
−0.5
−1.0
10
20
30
40
50
60
t

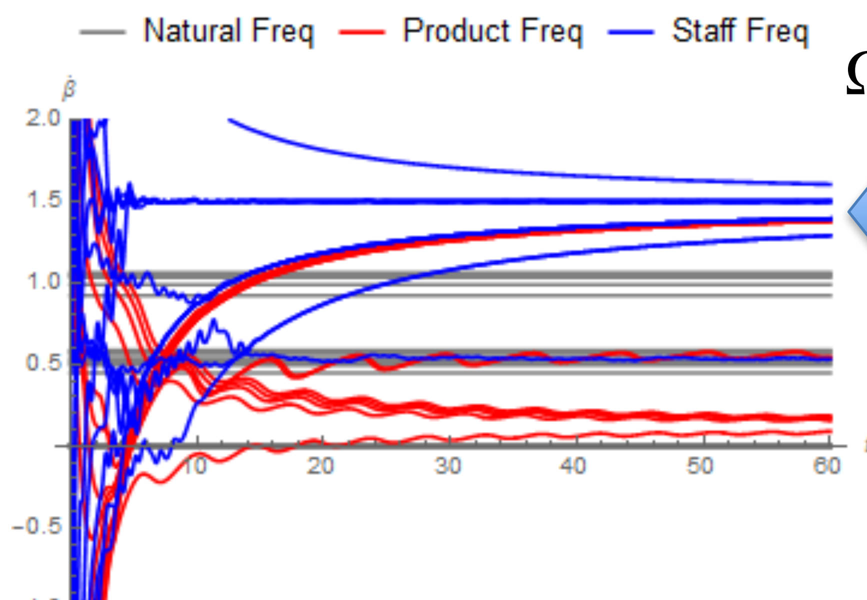
High freq driver





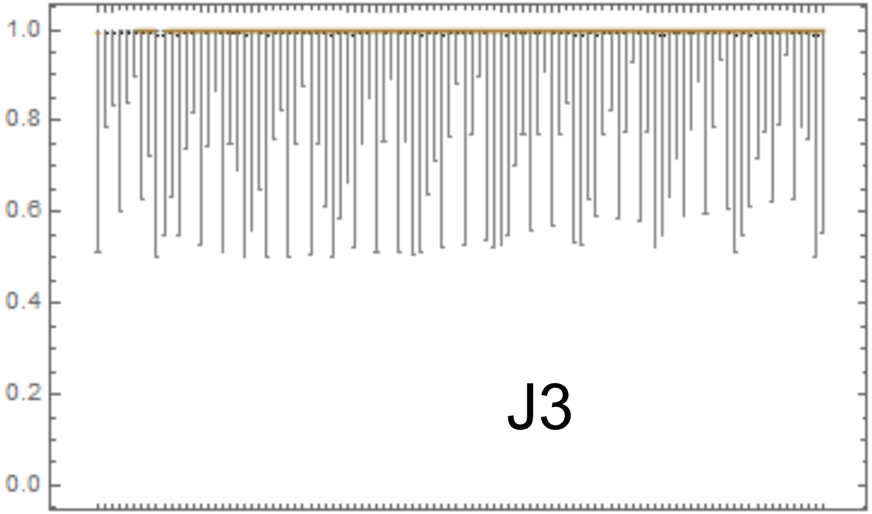
ρ=0.45

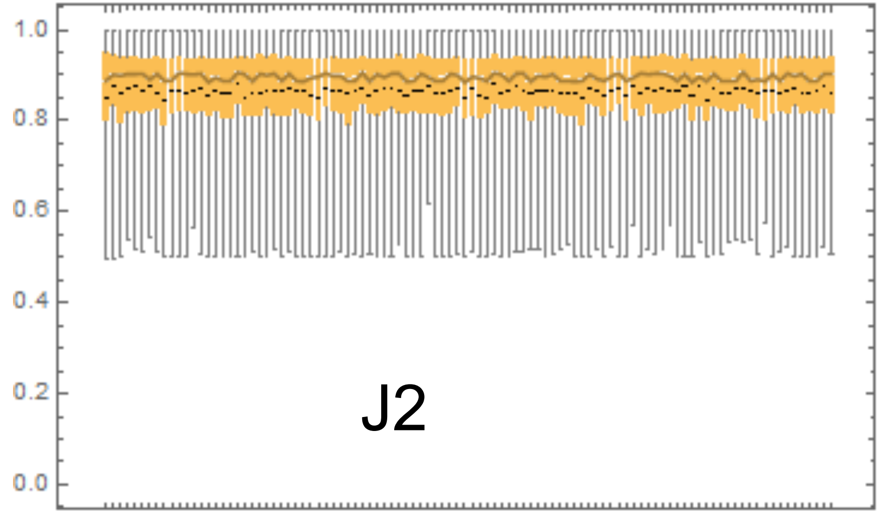
Ω=1.5

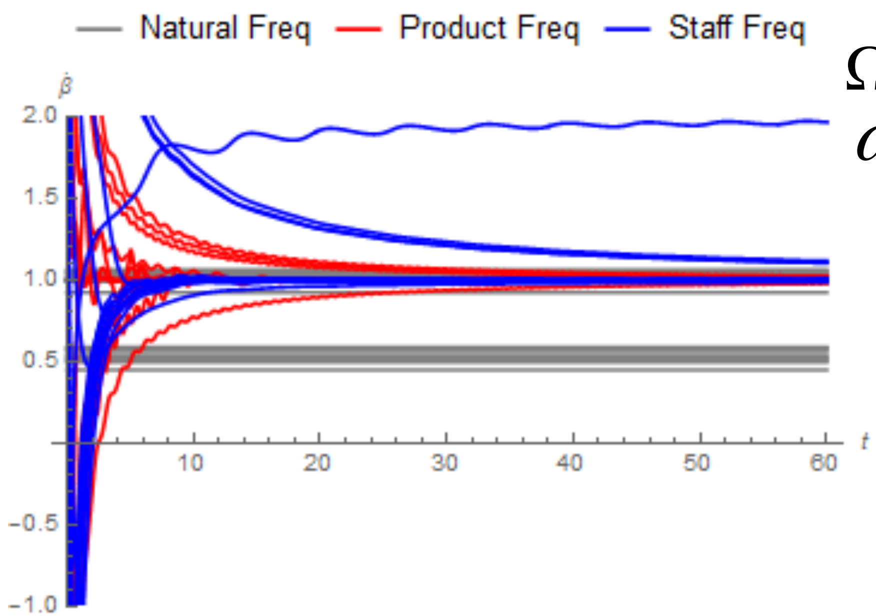


"Not bad" – some people fast; reasonable sync with info. But J2 poor.

Smart IO and control



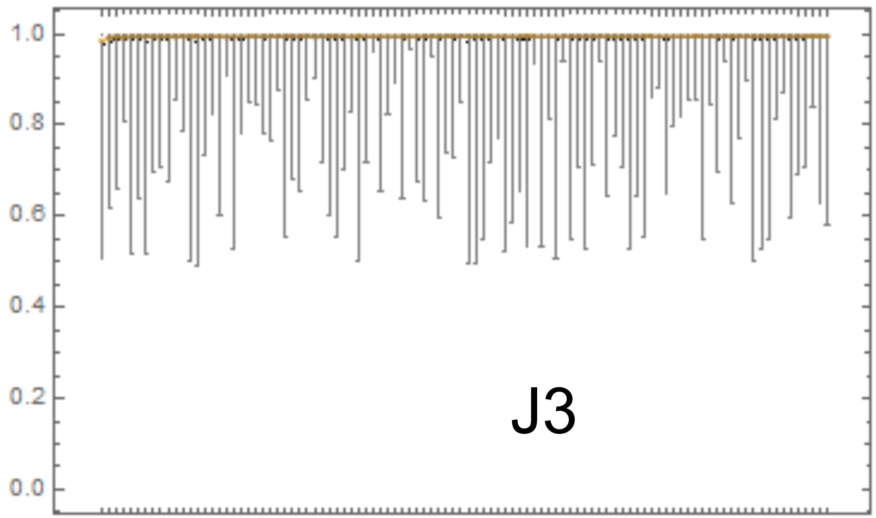


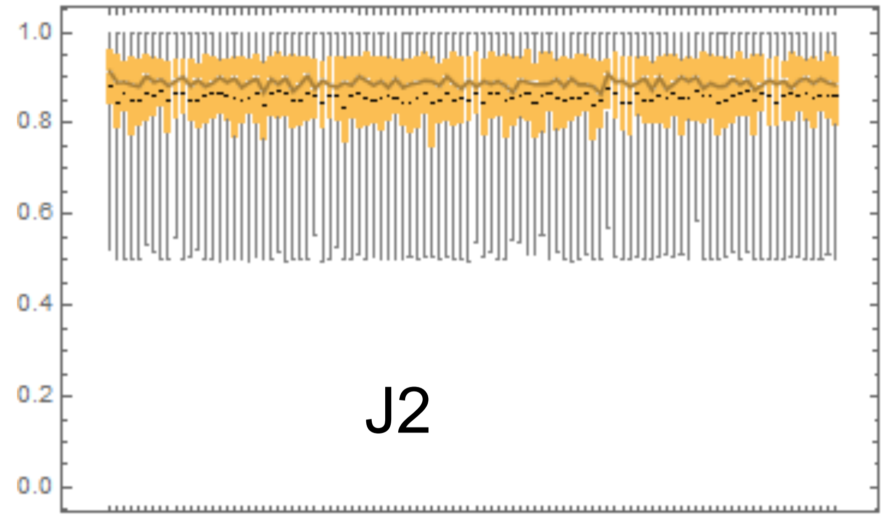


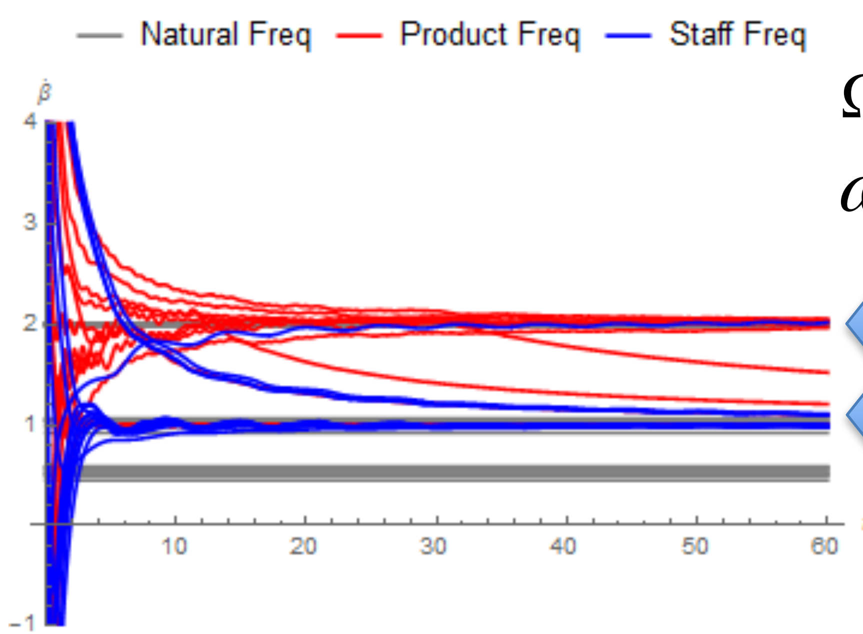
Ω=1.5

$\omega_{IO} = 1$

Smart *fast* IO





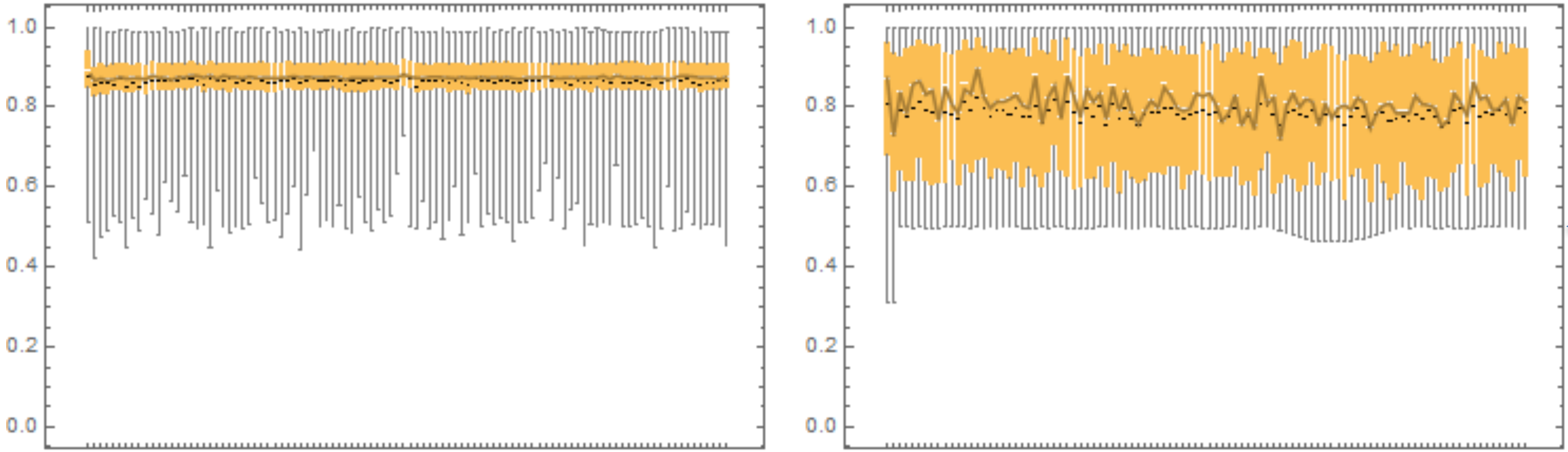


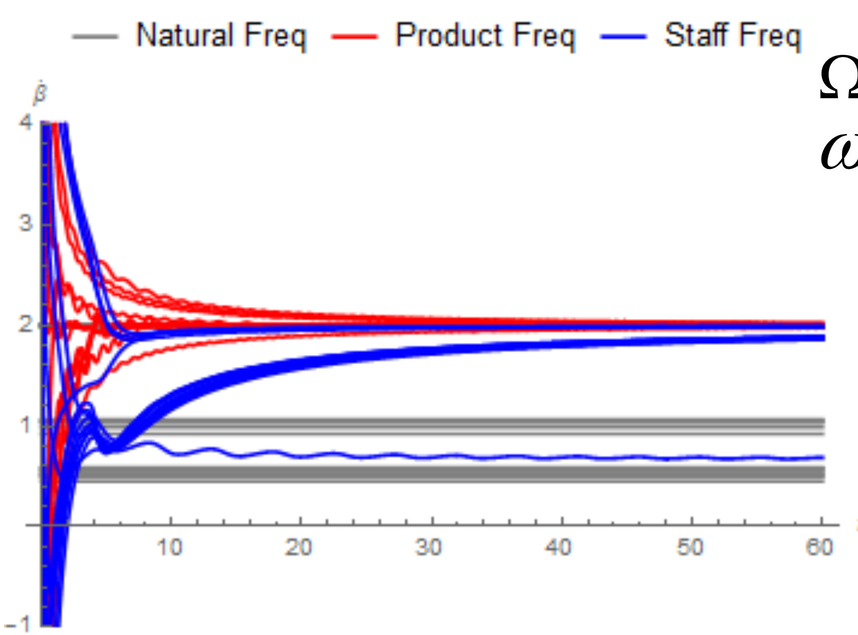
$\Omega=1$

$\omega_{IO} = 2$

Best overall on balance

Smart fast IO driven fast





Ω=2

$\omega_{IO} = 2$

Best instance!
But exceptions worse

Conclusions

- Model for headquarters staff based on synchronising decision loops calibrated to routine business correctly displays probability of incoherence in a Crisis, consistent with Contingency Theory as consequence of higher organisational centralisation.

- The model provides a natural formalism for modelling some aspects of complex human decision making in socio-technical systems: self-synchronisation, networks, probabilistic behaviours, and 'jumps' in decision processes due to urgency of environment.

- ***Many key behaviours can be analytically derived using fixed-point analysis close to synchrony: "organisational theory on the back of an envelope".***

- The model has predictive power: human and technological components may be modelled with minimal explicit parameters or via probability distributions.

- AI agents may be straightforwardly represented at the same level of fidelity as human agents with enough characteristics that they may be distinguished.

- Therefore, Whole-of-System dynamics may be tested.

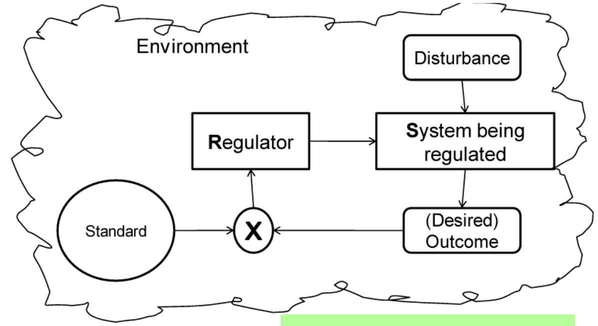
- **Clear evidence that AI is not a universal panacea – points of imbalance in relationship to human agents may be detected and lead to clear instabilities.**

- **Smart enabled information objects with adaptive control mechanisms help achieve such a balance.**

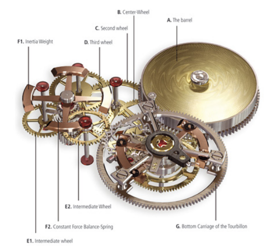
Appendix

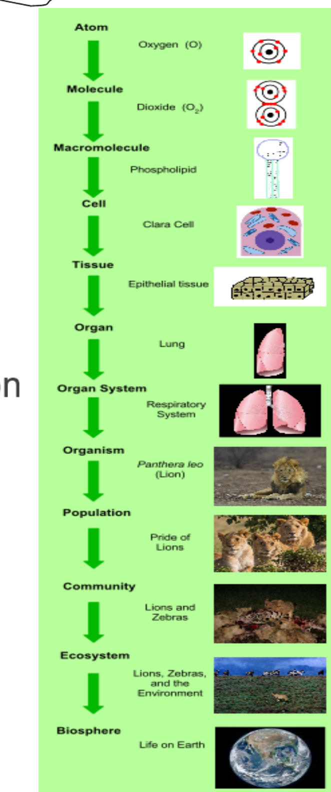
Human Organisation and Complexity

- W. Ross Ashby, Principle of Requisite Variety (1958): Control of ‘complex systems’; Conant-Ashby theorem (1970): biological, social systems



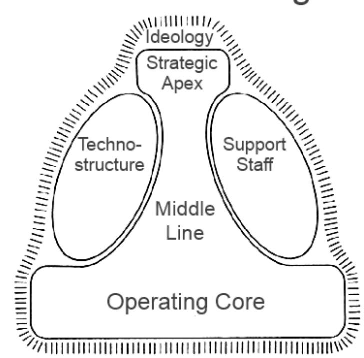
- Herb Simon, *Architecture of Complexity* (1962): value of hierarchy as ‘nearly decomposable systems’; organisations as instances in span from physical, chemical, biological, social





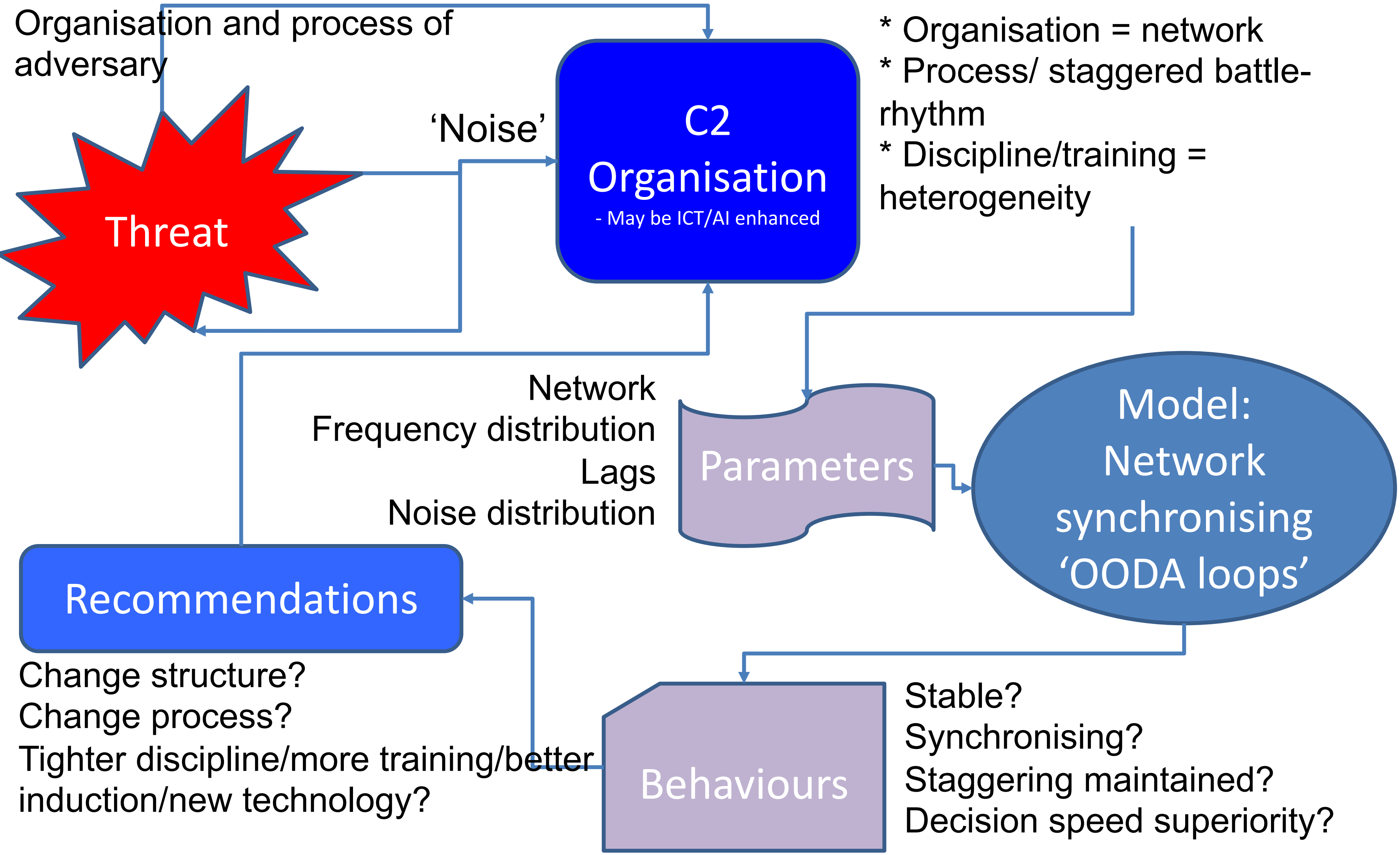
- Henry Mintzberg, The Structuring of Organizations (1979): empirical theory for range of structures & fitness-for-purpose

Six Basic Parts of the Organization



Key concepts: network structures, heavy tails, bounded rationality, the role of environment

Use-case


Organisation and process of adversary
Threat
'Noise'
C2 Organisation
- May be ICT/AI enhanced
* Organisation = network
* Process/ staggered battle-rhythm
* Discipline/training = heterogeneity
Network
Frequency distribution
Lags
Noise distribution
Parameters
Model: Network synchronising 'OODA loops'
Recommendations
Change structure?
Change process?
Tighter discipline/more training/better induction/new technology?
Behaviours
Stable?
Synchronising?
Staggering maintained?
Decision speed superiority?

Stochastic Kuramoto model

$$d\theta_i(t) = \omega_i dt + K\sum_j A_{ij}\sin(\theta_j(t)-\theta_i(t))dt + dL_i(t)$$

Noise is proxy for complexity of environment

Typically (Bag et al 2007; Khobasht et al; Esfahani et al 2012):

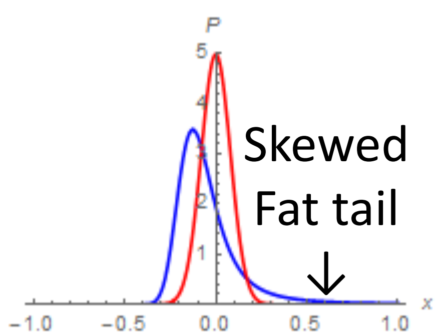
$$L_i(t) = \sigma\sqrt{t}Z_i,\ Z_i \in N(0,1) \text{ or } U(0,1)$$

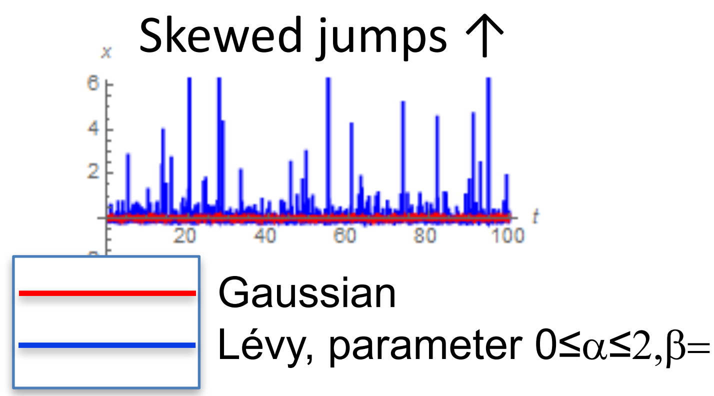
Here: *L(t)* = skewed stable Lévy noise (Kalloniatis & Roberts PhysA 2017)

Characteristic function & Prob Density Function:

$$\varphi_X(t) = \mathrm{E}[e^{itX}] = \int e^{itx}P_X(x) = \mathsf{F}[P_X(x)]$$

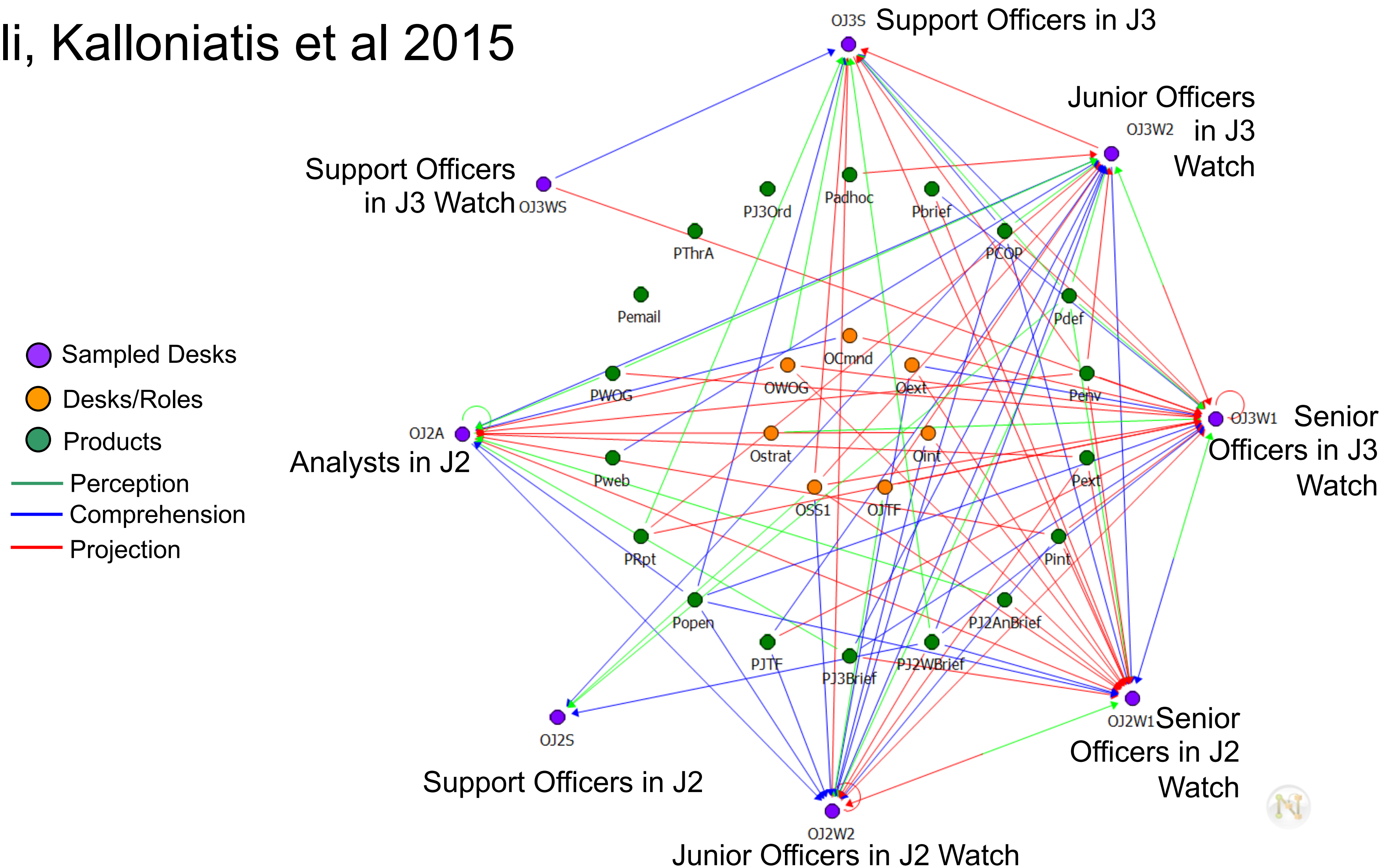
$$N(\mu,\sigma^2) : \varphi(k) = e^{ik\mu-\frac{1}{2}\sigma^2k^2} \rightarrow e^{ik\mu-\frac{1}{2}\sigma^2|k|^\alpha} \rightarrow e^{ik\mu-\frac{1}{2}\sigma^2|k|^\alpha(1-i\beta\tan(\frac{\pi\alpha}{2})\mathrm{sgn}(k))} : L(\alpha,\mu,\sigma^2,\beta)$$





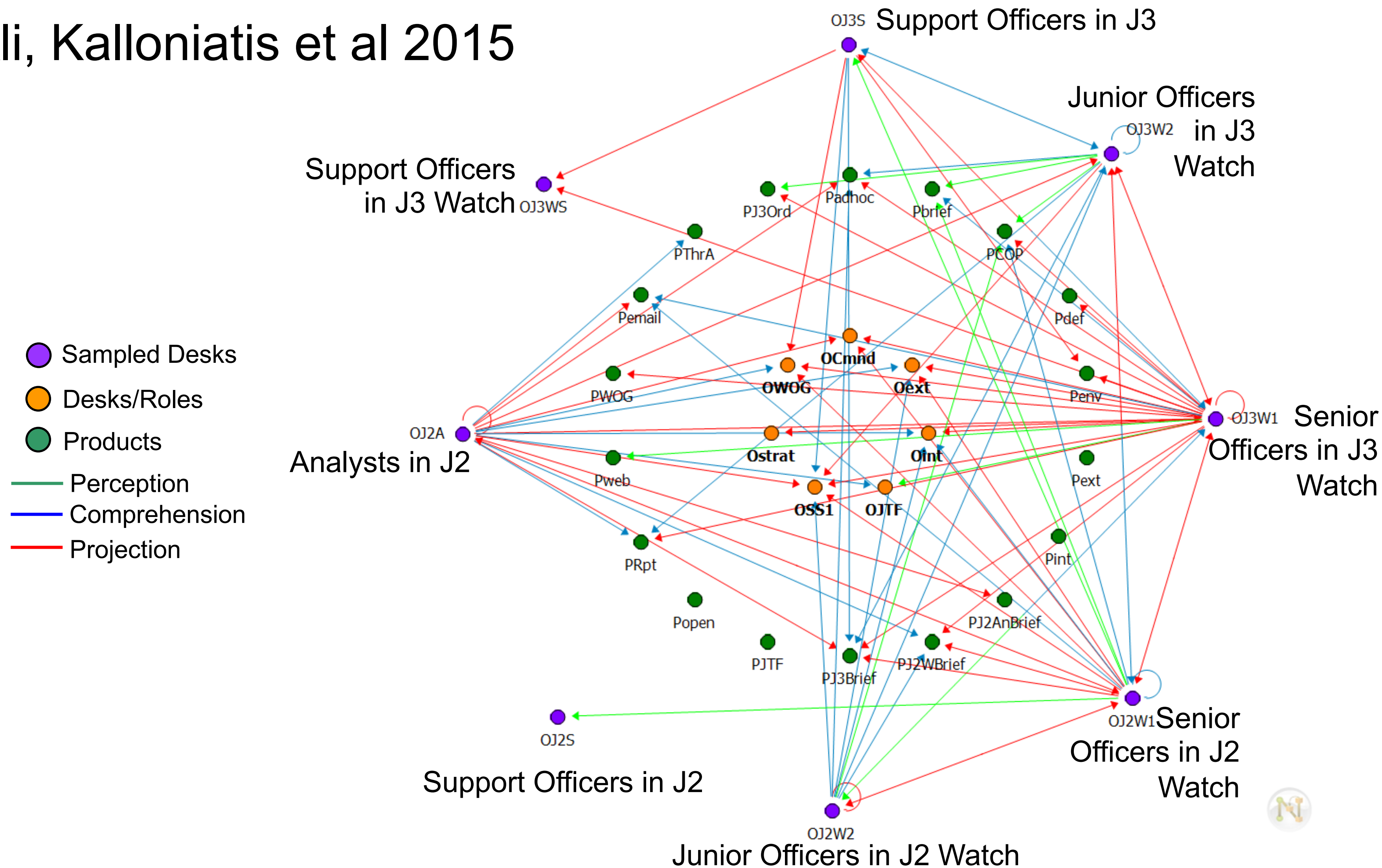
SAWN for Steady-State activity: Pull

Ali, Kalloniatis et al 2015



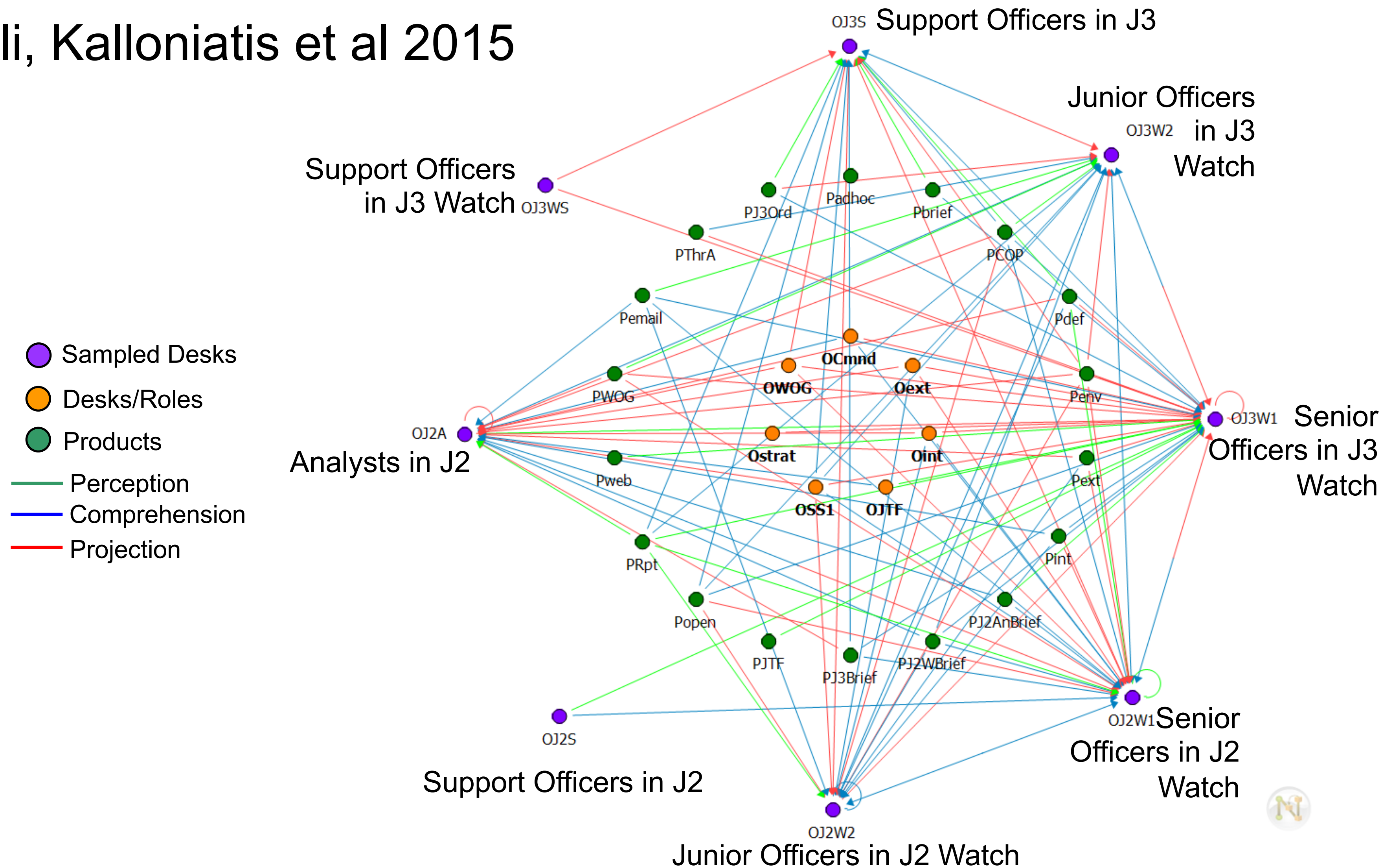
SAWN for Steady-State activity: Push

Ali, Kalloniatis et al 2015



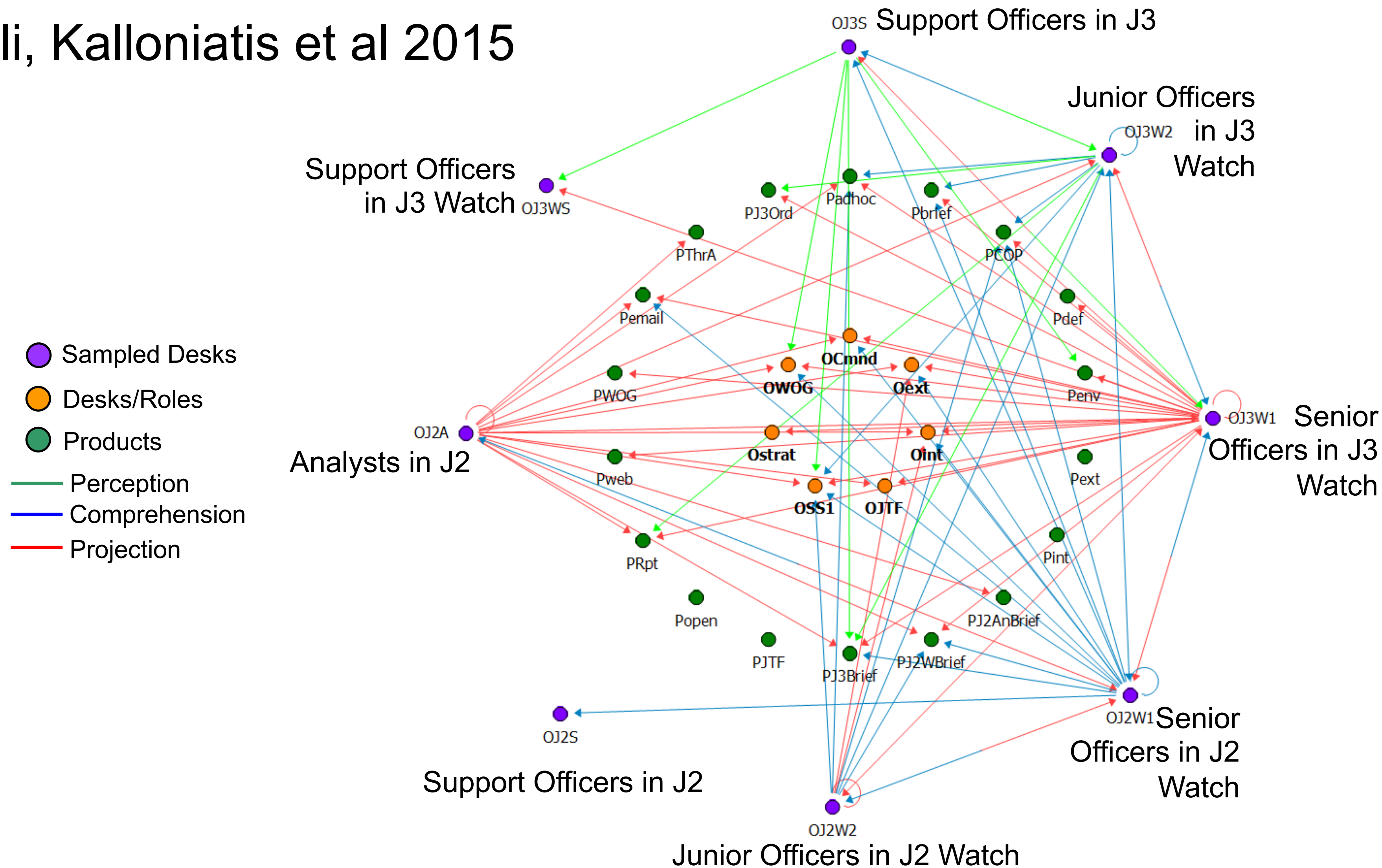
SAWN for Crisis activity: Pull

Ali, Kalloniatis et al 2015



SAWN for Crisis activity: Push

Ali, Kalloniatis et al 2015



Key properties of Lévy noise

Stable property $$aX_1 + bX_2 \overset{dist}{=} cX + d$$

CLT: $$\sqrt{n}\left[\frac{1}{n}\sum_{i=1}^{n} X_i - \mu\right] \overset{dist}{=} N(0,\sigma^2) \qquad \mu, \sigma < \infty$$

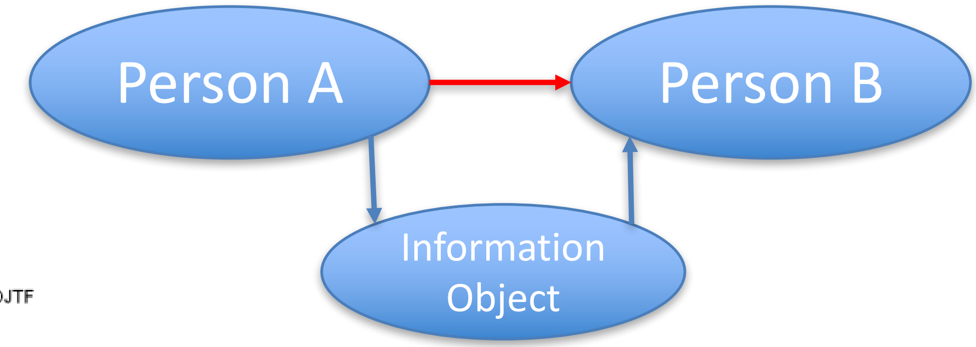
Lévy stable case: $$X_1 + \ldots + X_n \overset{dist}{=} n^{1/\alpha} X_1 + \mu(n - n^{1/\alpha})$$

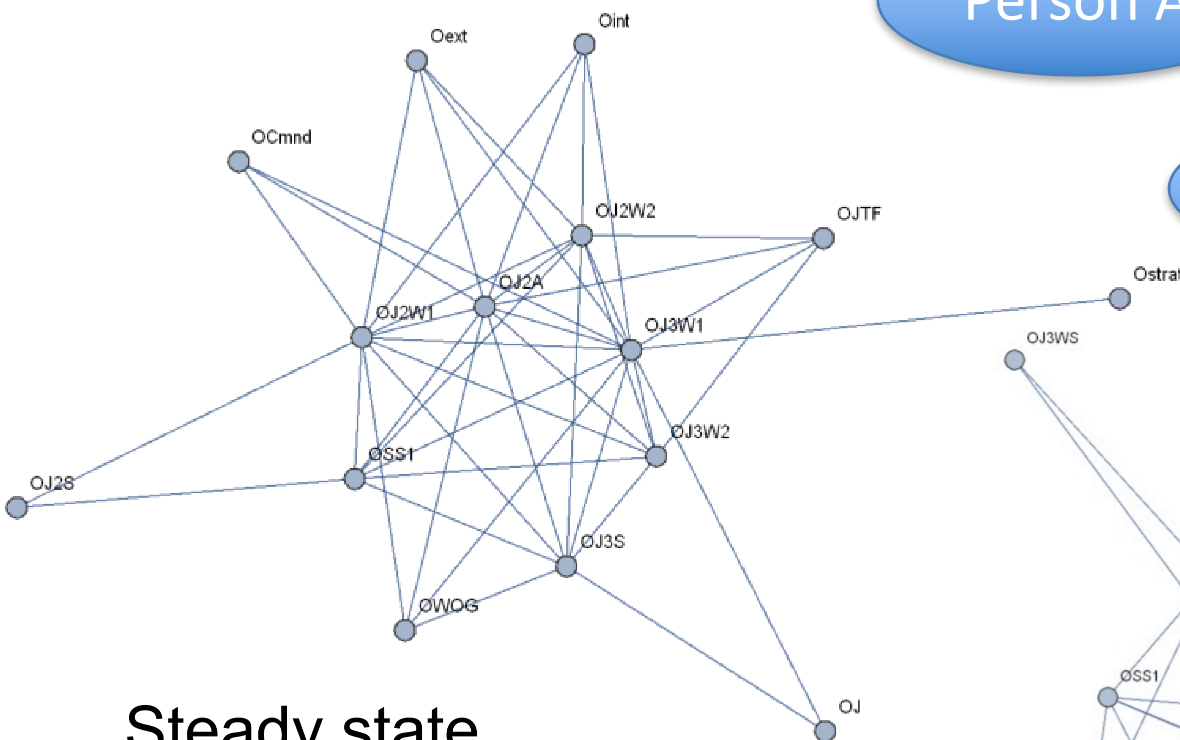
- 1<α<2: in limit - *finite* mean, *infinite* variance
- 0<α< 1:in limit - *infinite* mean and *infinite* variance

Characteristic function
& Prob Density Function: $$\varphi_X(t) = \mathrm{E}[e^{itX}] = \int_R e^{itx} P_X(x) = F_t[P_X(x)]$$

$$N(\mu,\sigma^2) : \varphi(t) = e^{it\mu - \frac{1}{2}\sigma^2 t^2} \rightarrow e^{it\mu - \frac{1}{2}\sigma^2 t^\alpha} \leftarrow \text{Levy}$$

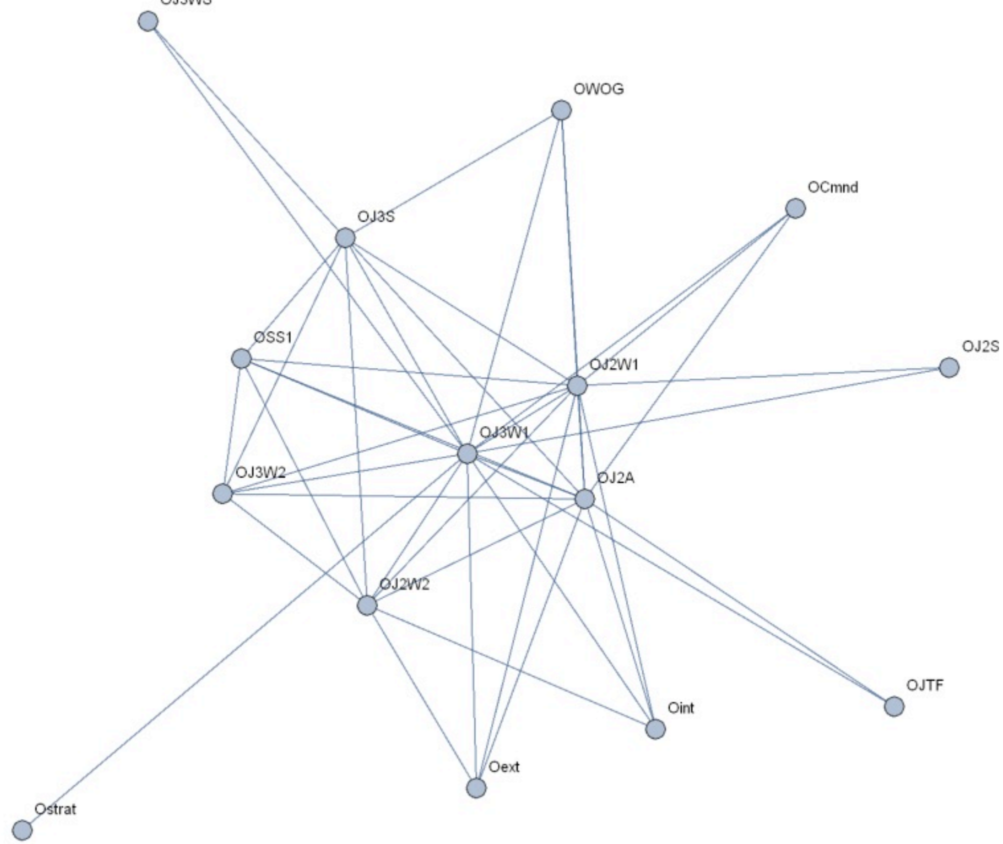
Pure social networks



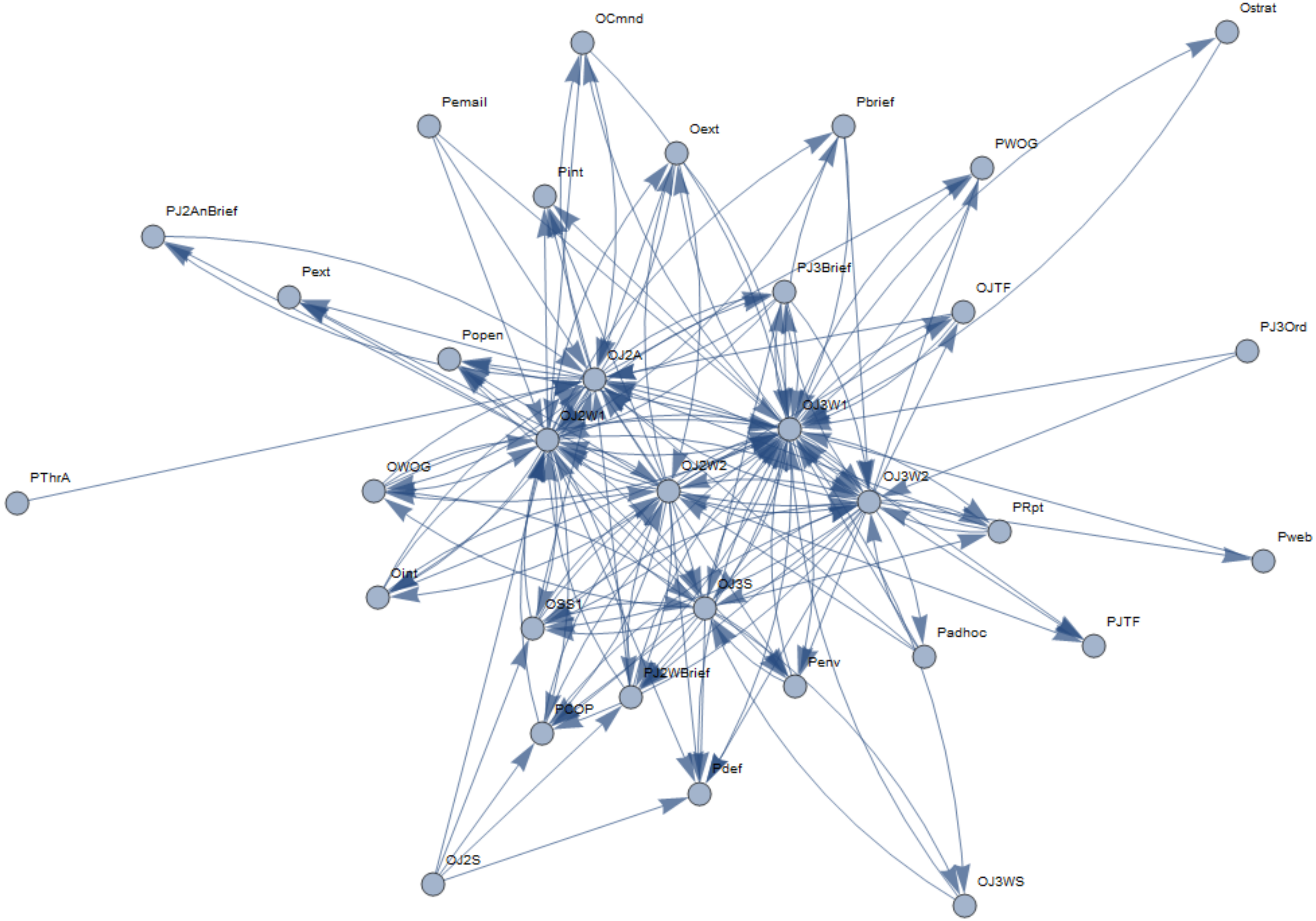


Steady state

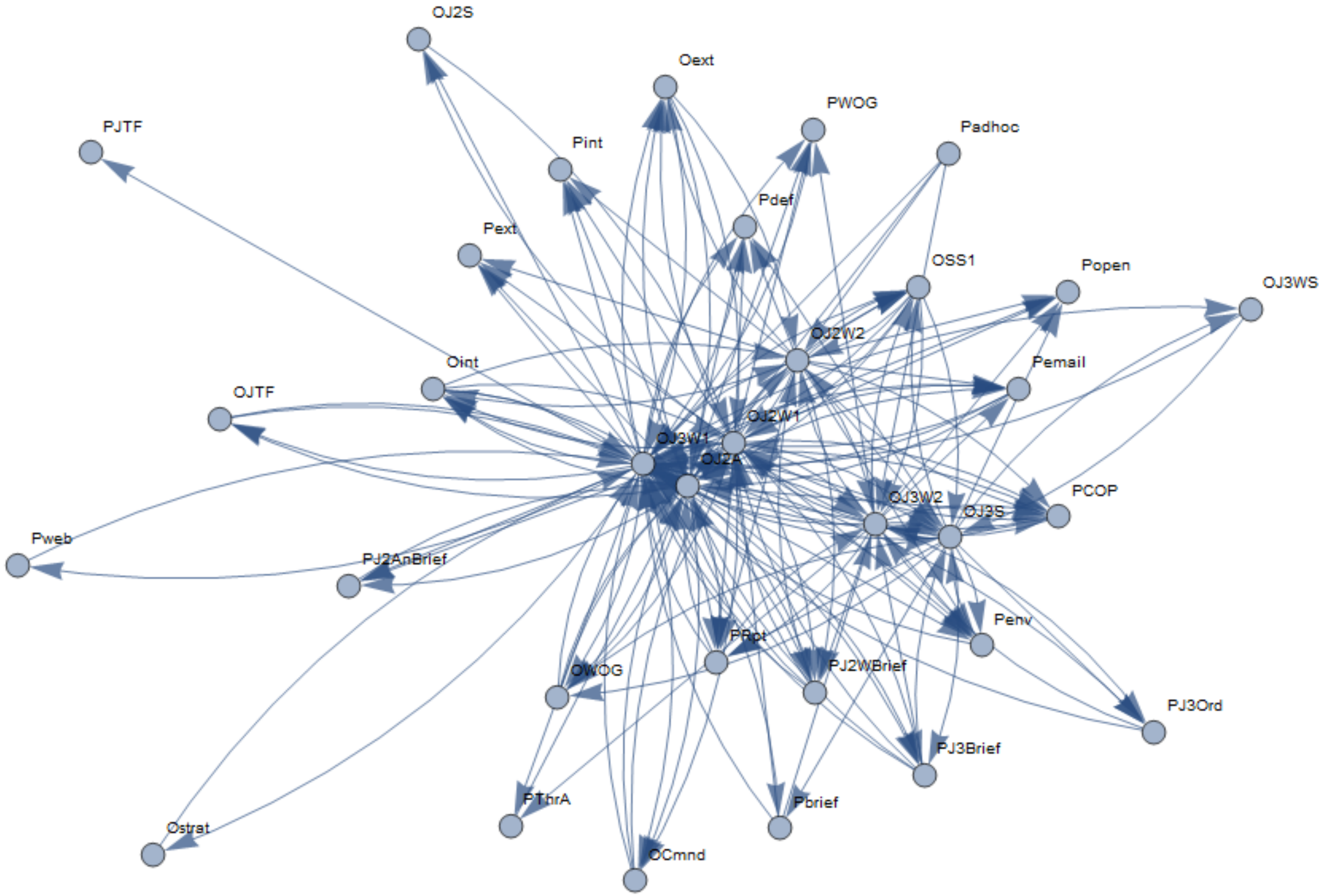
Crisis



Directed Graphs – Steady State

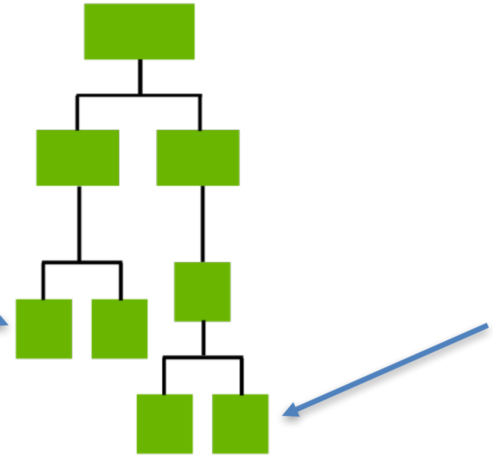


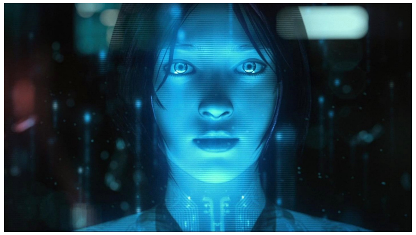
Directed Graphs – Crisis



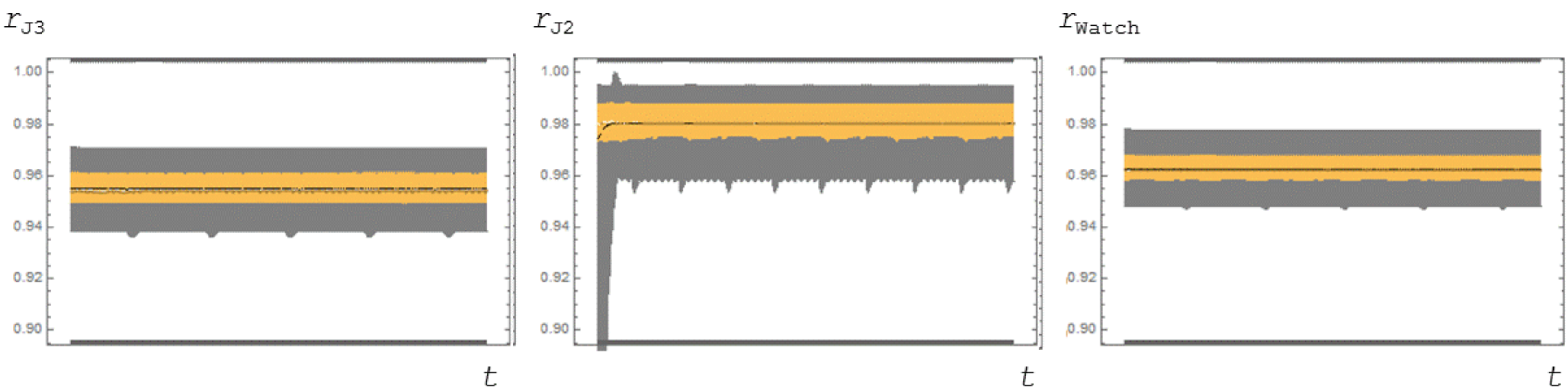
Interventions II: AI – 'noiseless' WKs

Kalloniatis, ICCRTS 2016



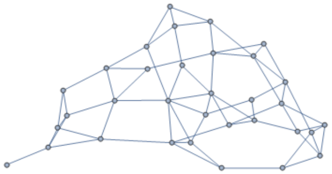


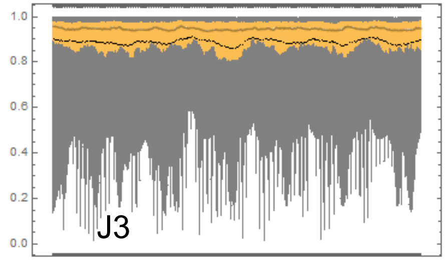
Lowest ranked staff in shift work often those of lowest morale.



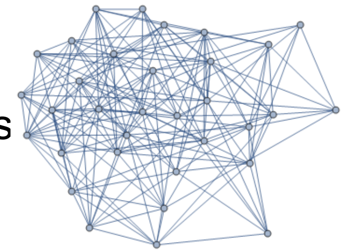
'***Sweet spot***': Interventions I + II –
smart I.O.s and AI lowest-ranked watch staff

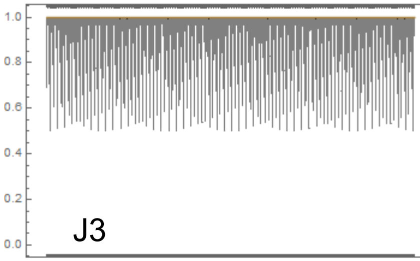
Small World, p=0.2



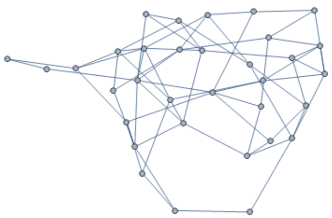


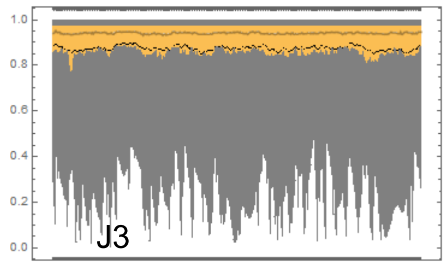
Erdos-Renyi, #edges =180



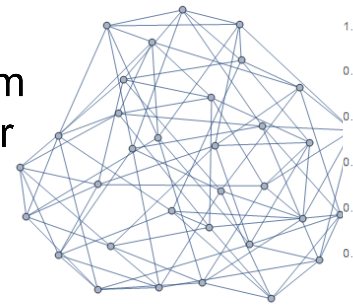


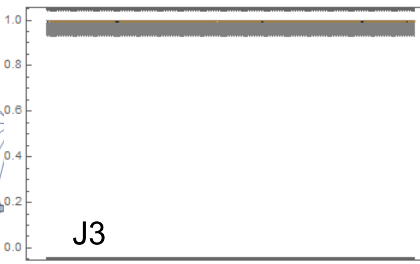
Small World, p=0.6



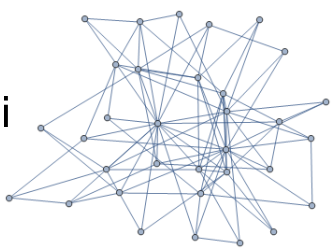


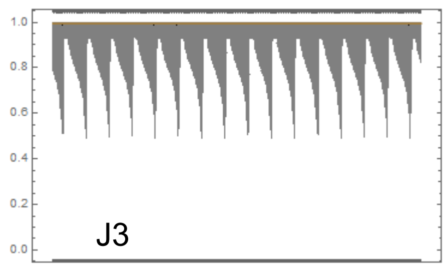
Random Regular av deg=6



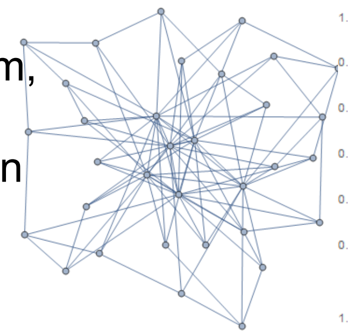


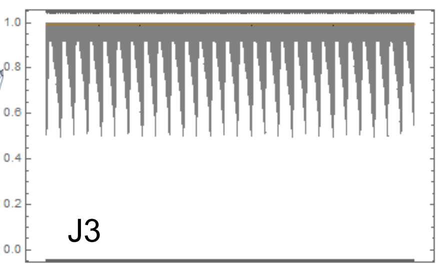
Barabasi -Alberts, m=3



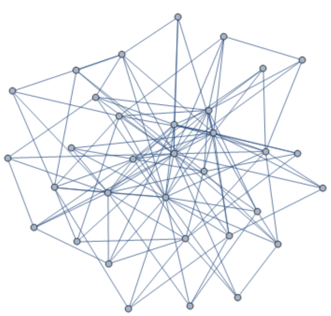


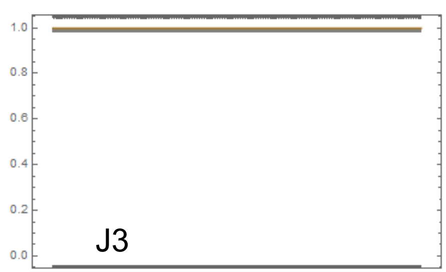
Random, Appr. Deg dsn 1



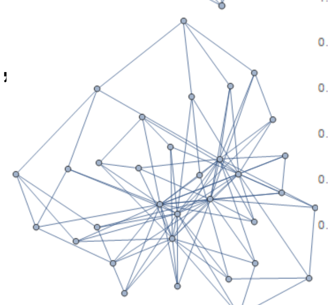


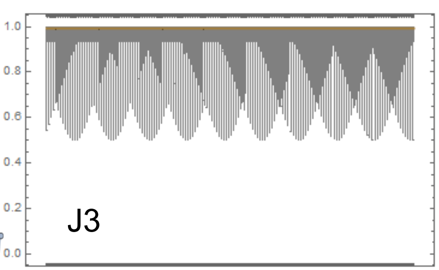
Barabasi -Alberts, m=4



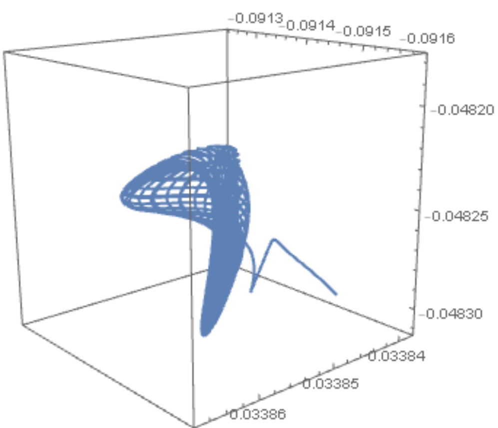


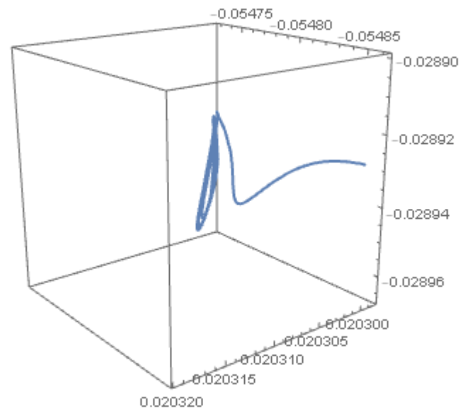
Random, Appr. Deg dsn 2



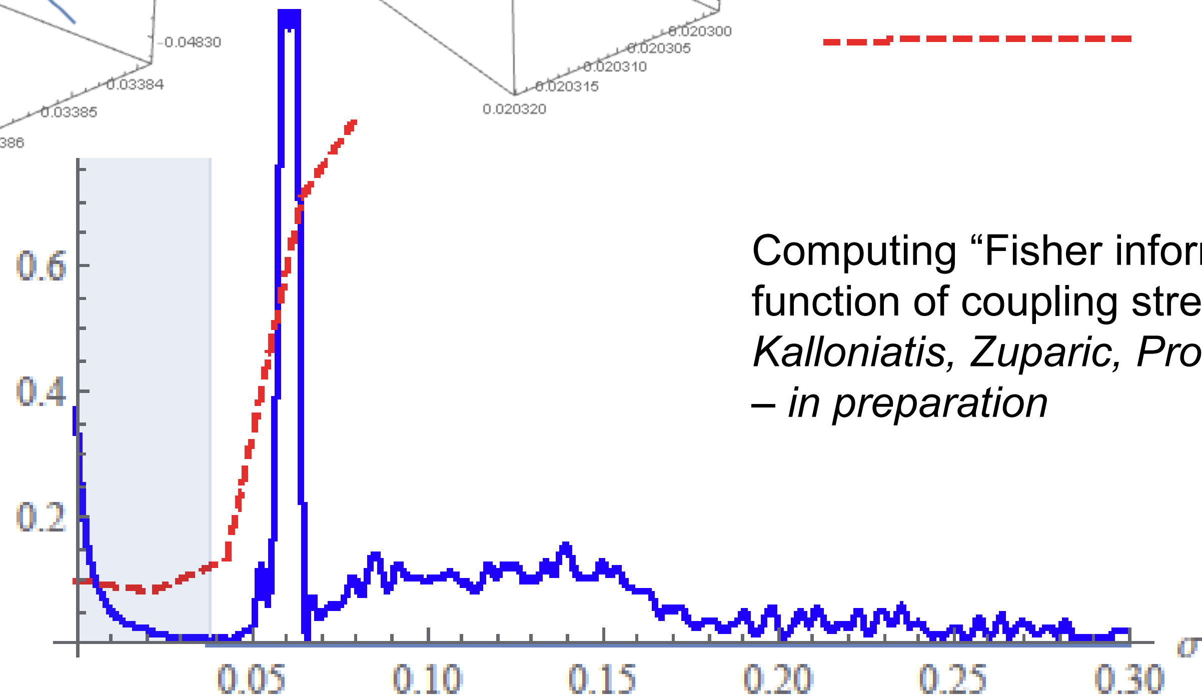


Beyond Metaphors: Are they ‘critical’? How close to ‘chaos’? Is there ‘entropy’?





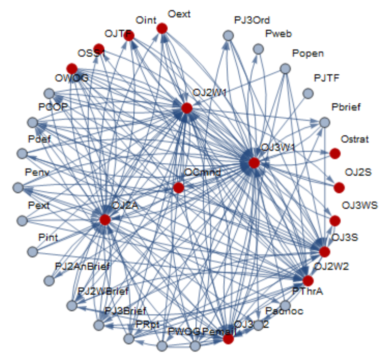
Phase profiles – based on Laplacian decomposition of dynamics

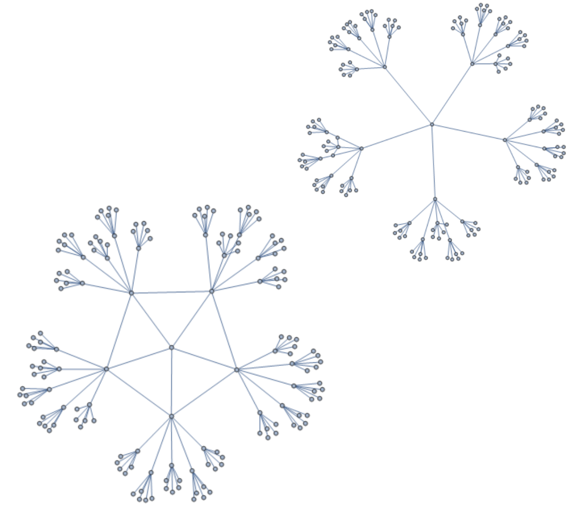


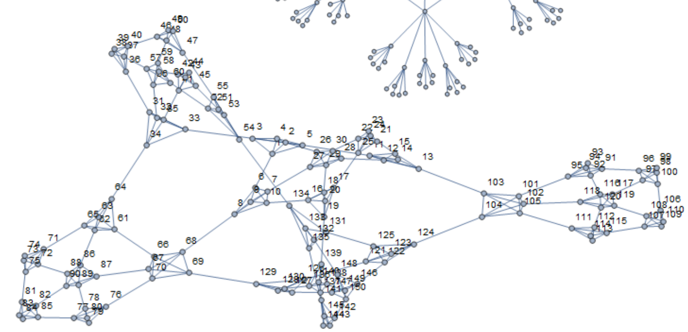
Computing “Fisher information” as function of coupling strength: *Kalloniatis, Zuparic, Prokopenko – in preparation*

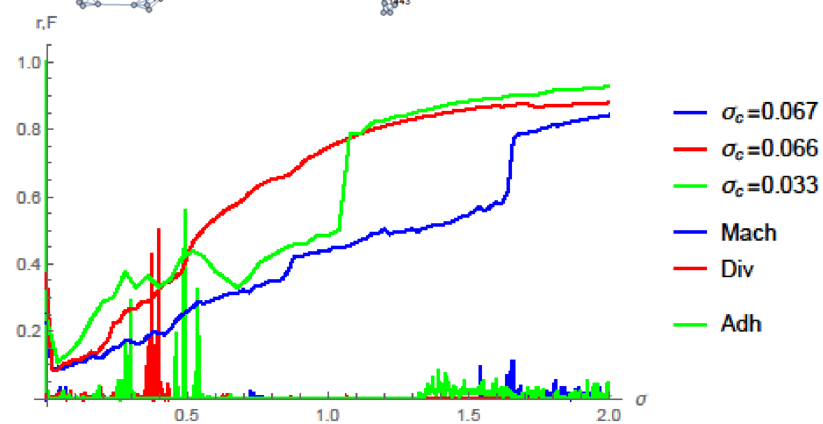
Caveats

- In fact, even **<u>this</u>** is too small, too structured to truly exhibit ‘chaoticity’ (3-4 clusters – periodic phase space orbits).
- In the real world, **<u>it</u>** resides in a much larger (N=600+ people*) quite hierarchical structure - comparatively large critical coupling – very hard to completely synchronise.
- Even with moderately large N≈150 classical organisation structures – Machine, Divisional, Hierarchical – signal for ‘phase transition’ is weak:









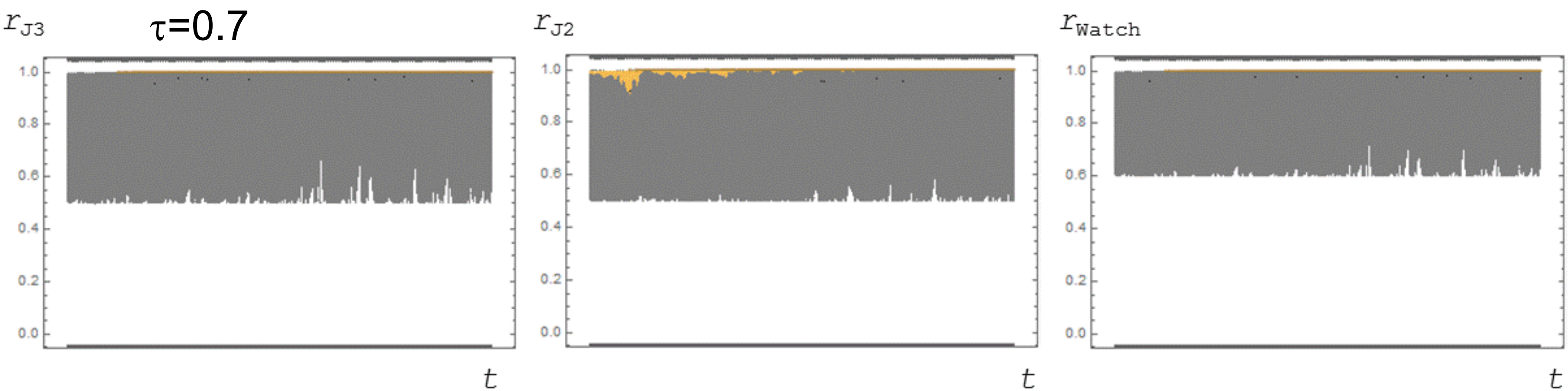
Interventions III: Adaptive lags

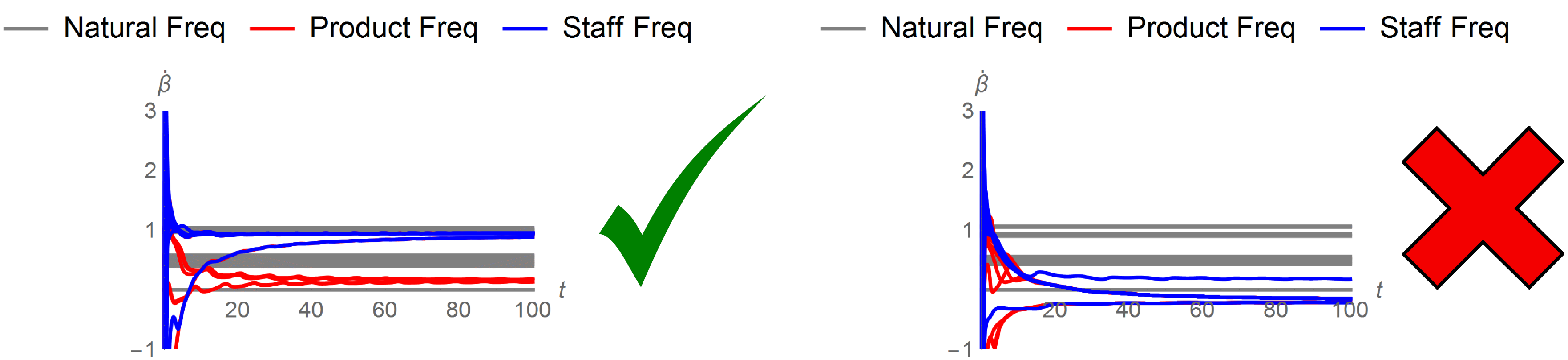
Brede & Kalloniatis 2016

$$\dot{\beta}_i = \omega_i + \sigma \sum_{j=1}^{N} A_{ij} \sin(\beta_j - \beta_i + \varphi_i)$$

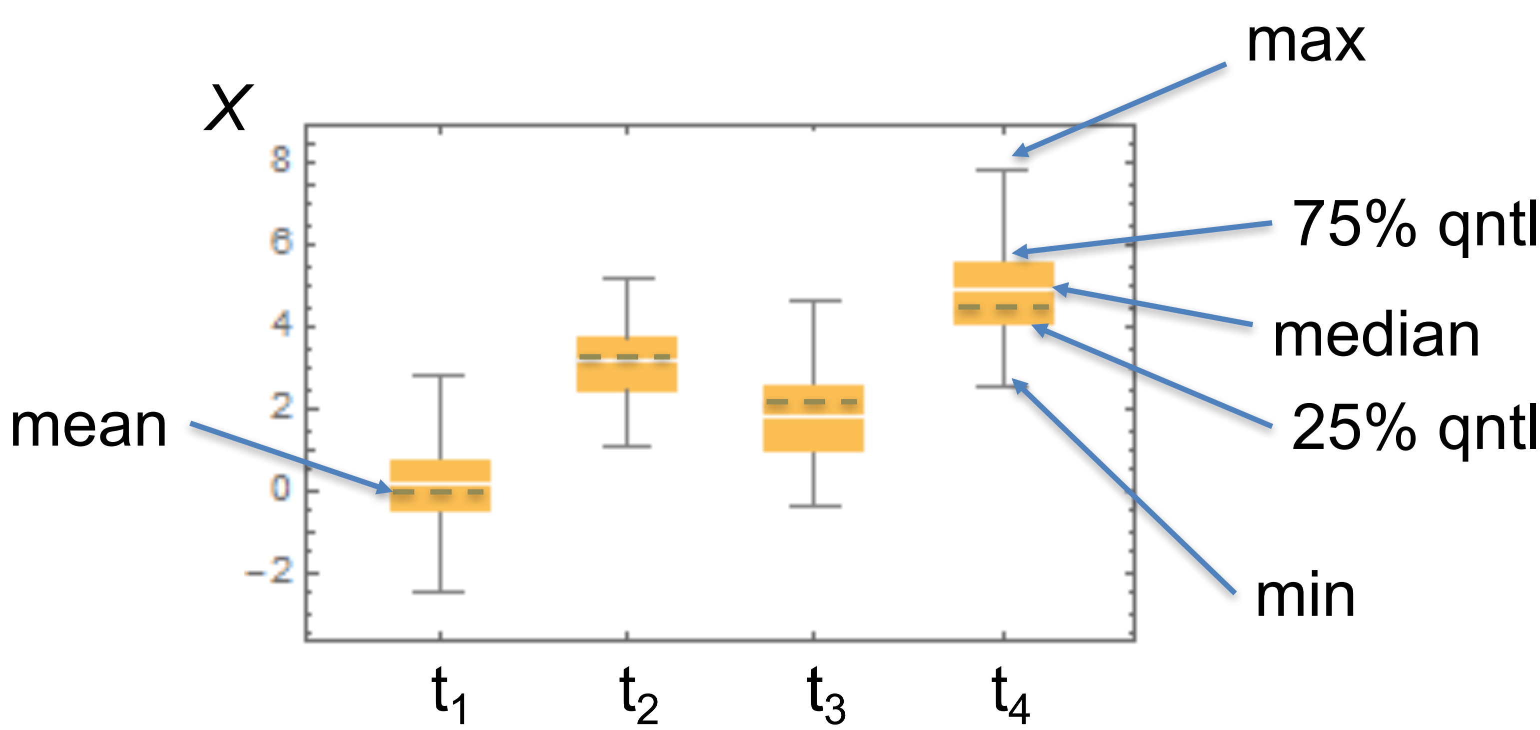
$$\dot{\varphi}_i = \tau \sum_{j=1}^{N} A_{ij} \sin(\beta_j - \beta_i).$$

Lags or ‘frustrations’:
Kuramoto-Sakaguchi model
But *dynamical*





Box-whisker plots

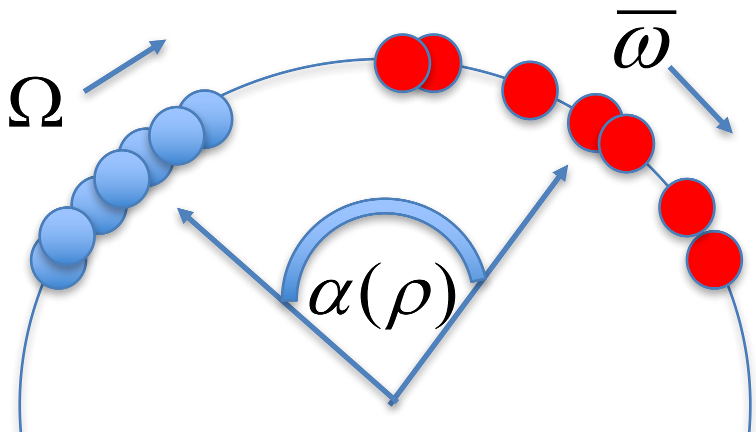


100 runs performed at each parameter setting

Origin of effect – eg random regular graphs

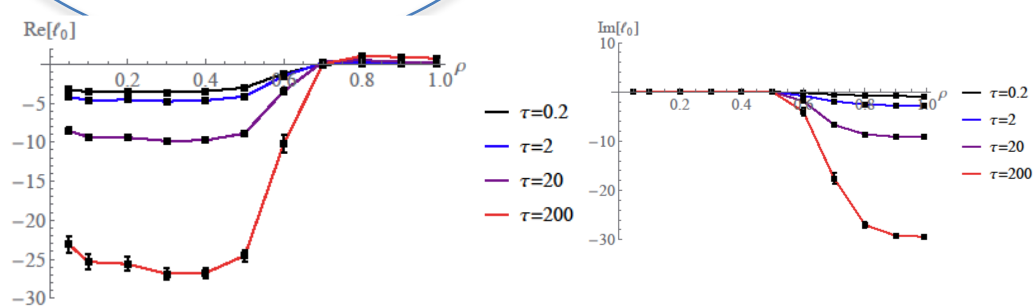
Uncontrolled

Controlled



Adaptive lags allow micro-mutual adjustment giving minimal splay and synch to driving freq.

When α is too large Lyapunov instability follows:



Uncontrolled self-synch to *mean freq* through ordinary Kuramoto mechanism with large 'splay'.