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Organisations, C2-Entropy and Military Command

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JOINT COMMAND ANALYSIS

Outline

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0. The elements of C2-Entropy
1. Historical Motivation
2. Theoretical Development of C2-Entropy Concept
3. Return to History
4. Implications for Future C2

(Appendix: Supplementary Material)

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Elements of the *C2-Entropy* Concept

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- ***C2-system:***
  - a statistical mechanical system with two classes of dynamical entities: *nodes and links*.

- ***C2-links:***
  - can exist at any time *without actual communication* in process
  - through *prior* distribution of information are created in a *latent* state
  - are exercised as degrees of freedom through operational communication
  - through continued activity undergo thermalisation/equilibration
  - have phase space dimensionality commensurate with means of technological enhancement.

- ***C2-Entropy:***
  - quantifies disorder across both node and link degrees of freedom
  - grows with time and activity but can be concentrated in one of or both C2-nodes and C2-links
  - minimal for particular degrees of freedom means relative controllability of those degrees of freedom
  - growth means overall loss of controllability of the system
  - is *maximal* at global equilibrium, least controllability: “system” must effectively be “re-initialised”.

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1. Historical Motivation

The Battle of the Milvian Bridge

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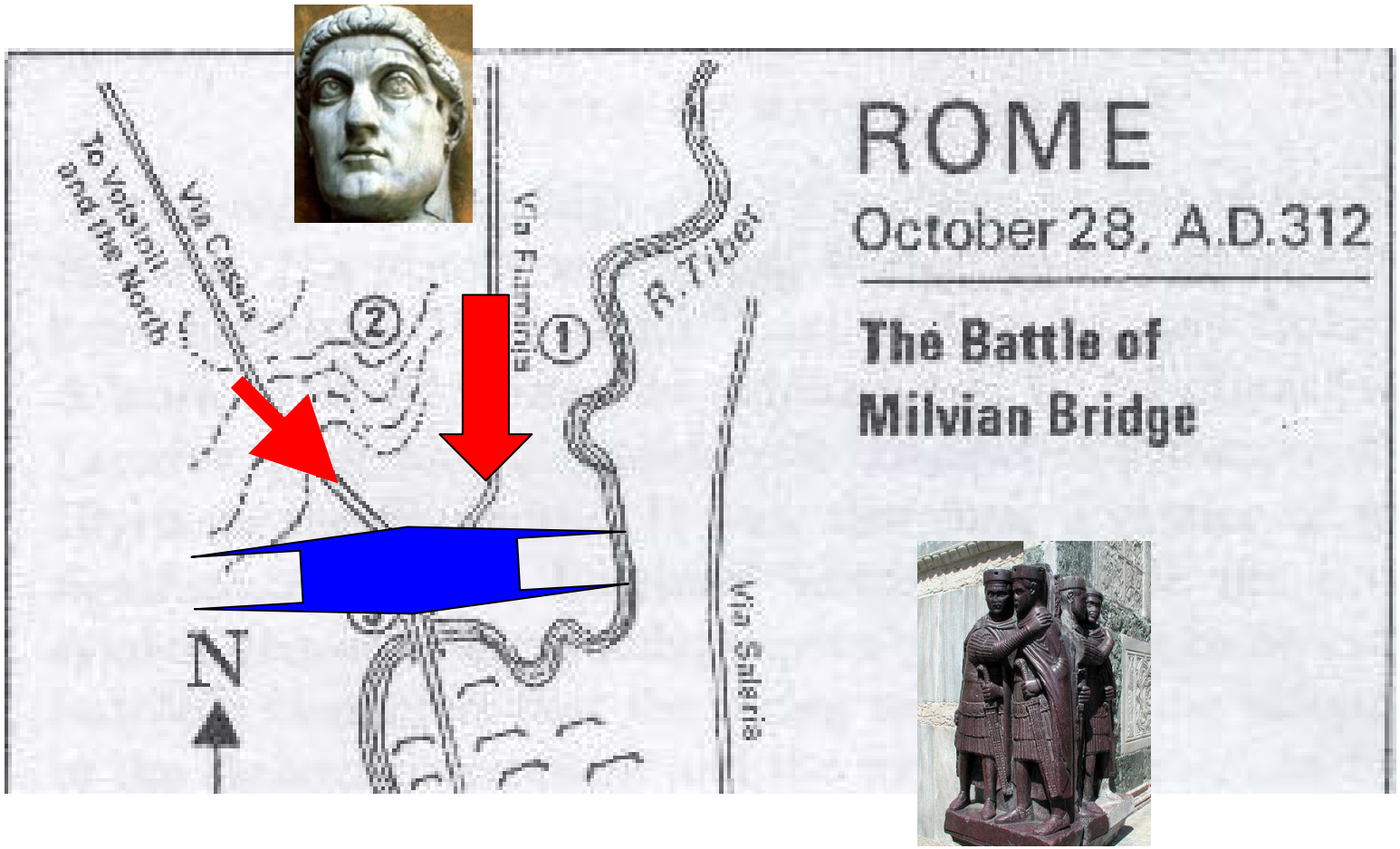

Constantine's army: approx. 40 000 men

Maxentius' army: approx. 80-100 000 men

Disorder in Space

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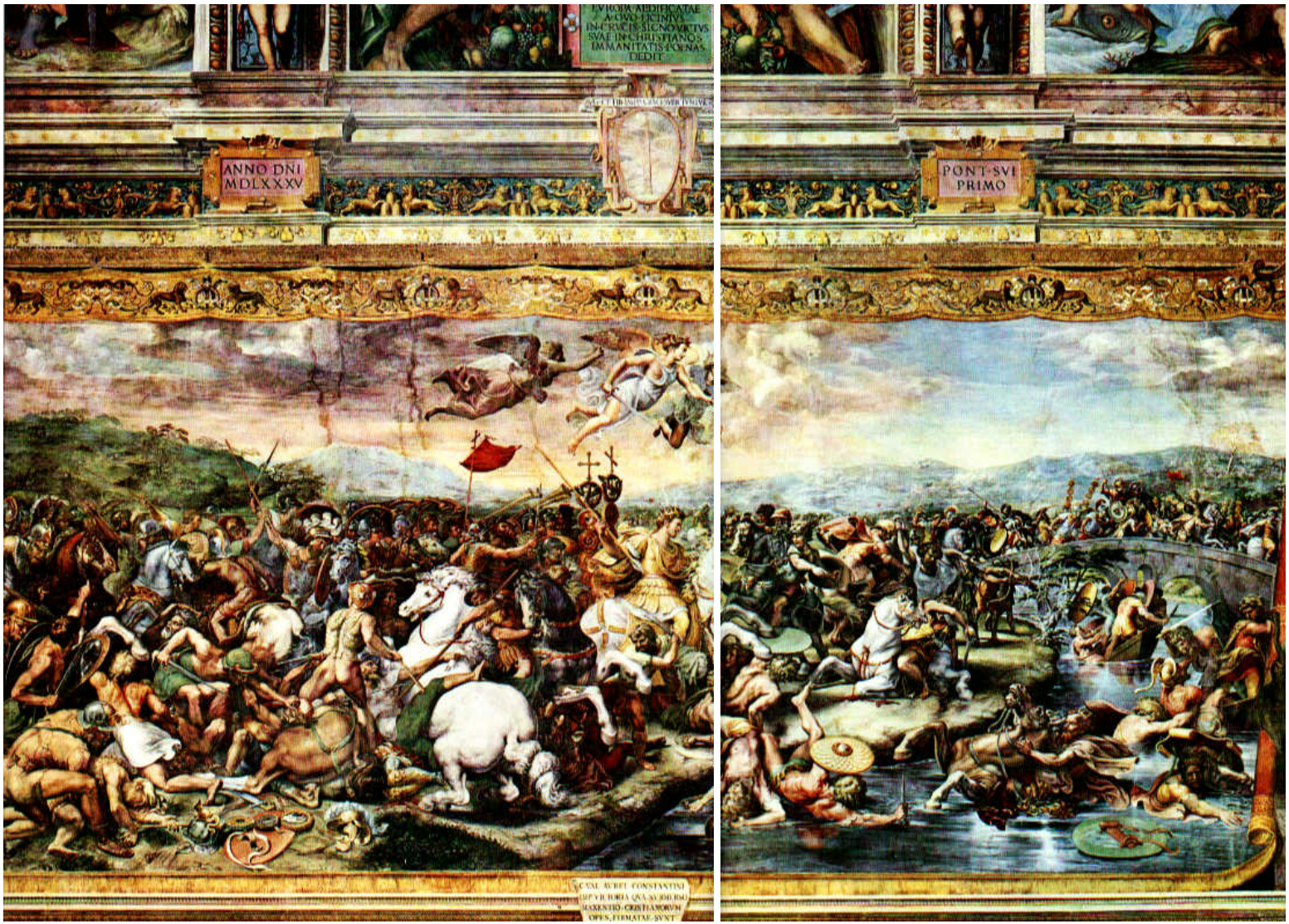

Sala di Constantino: Vatican

Irreversibility in War

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"… **as long as** Maxentius' cavalry offered resistance **there seemed some hope** left for him. **But** when his horsemen gave up **he took to flight** along with the rest and made for the city via the bridge across the river the timbers could not sustain the pressure of the host, but broke …"

Zosimus, Historia Nova

= Maxentius' defeat was irreversible after capitulation of cavalry.

… there is no other general measure for the irreversibility of a process than the amount of increase in entropy.

Max Planck, 1905.

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C2 and Maxentius' Defeat

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- Entropy of Maxentius' army *increased* with time: *spatial disorder*.
- C2-system was *available* (Roman military doctrine, chain of command, primitive comms) but not used.
- **C2 can reverse spatial disorder – *does this contradict growing entropy*?**
- ***Not necessarily: C2 degrees of freedom are part of the system.***

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2. Theoretical Considerations

Command and Control

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"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)

- The Commander:
  - Observes
  - Influences

the system.

Correctly identify the system state

Within a specific *aggregation* of the system.

"PARTITION"

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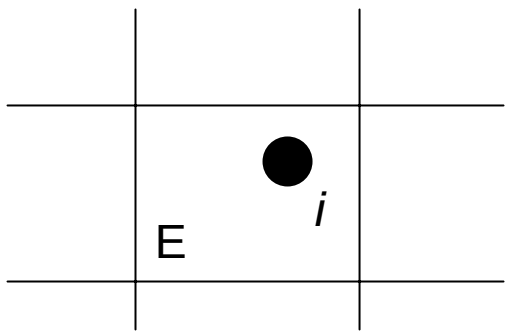
What is Entropy?

Loosely: “disorder”=difficulty in determining precise system state.

Boltzmann: $$S(E) = -\ln p(i \mid E)$$

Probability that system microstate *i* is in macrostate *E*

$$p(i \mid E)$$



Encodes the “cost-benefit” of partitioning a system in a particular way.

Average entropy: $$\bar{S} = -\sum_{E} p(i \mid E) \ln p(i \mid E)$$

From Engines to Organisations

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1870s

Thermodynamics	Statistical Mechanics
Macroscopic behaviour at *Equilibrium*	Microscopic behaviour *approaching Equilibrium*
Heat, Temperature	Molecular speed/energy distributions
2nd Law of Thermodynamics **ENTROPY**	Boltzmann's H-Law **ENTROPY**
	Shannon Information: probability of 1,0 in bit-string
Jayne's Maximum Entropy Principle	Jayne's Generalised System Statistical Mechanics
	Kolmogorov-Sinai Entropy
Berniker ***Organisational*** Thermodynamics	
	Ingber's Statistical Mechanical Combat Model
	C2-ENTROPY

Parkinson's Law(s) (1920s): ***Work* Expands to fill available *Capacity*;**

1940s

1950s

(1990s) ***Communication* Expands to fill available *Capacity*.**

Perrow's (1970s) **Normal Accident Theory**: Interactive Complexity vs Coupling

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Dynamics, Entropy and Phase Space

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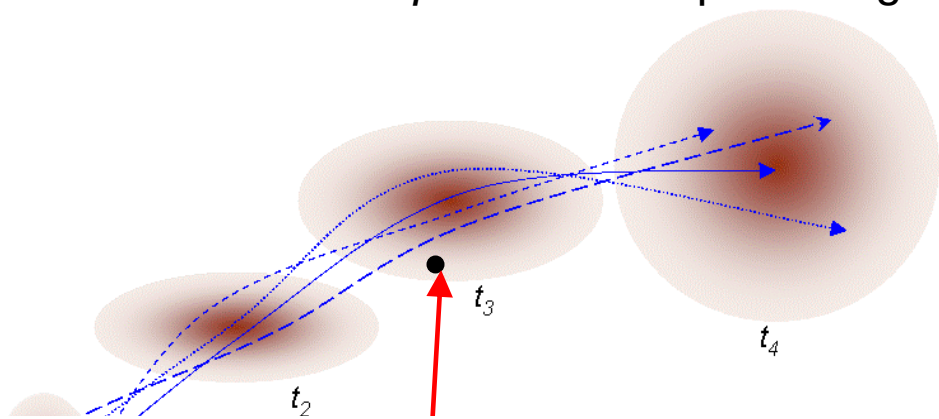
Equilibrium:
uniform distribution, unchanging in time *despite* microscopic changes.

Momentum

Non-equilibrium:
aggregate distribution *changes* with microscopic changes



If a system has *available* degrees of freedom, it will eventually *exercise* them.

Latency: *restrained* exercise of *available* degrees of freedom until *late* in dynamical evolution of system.

Military language: Capacity to *surge* in certain degrees of freedom.

Entropy and Control

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Maximum Entropy

=

Least chance of correctly determining system state by random selection inside a partition cell

=

Least Capacity to Control

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Caveats on defining the System

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- Boundaries: what is in (System) and what is out (Environment).
- Closure.
- E.L. Khalil's distinction between
  - System Dynamics (oscillations, abrupt, intermittent phenomena in time)
  - System Development (purposeful preparation in time).
- Latter defines System History initial and final point.

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3. Back to History

Disorder at *Milvio*: Determine the system state

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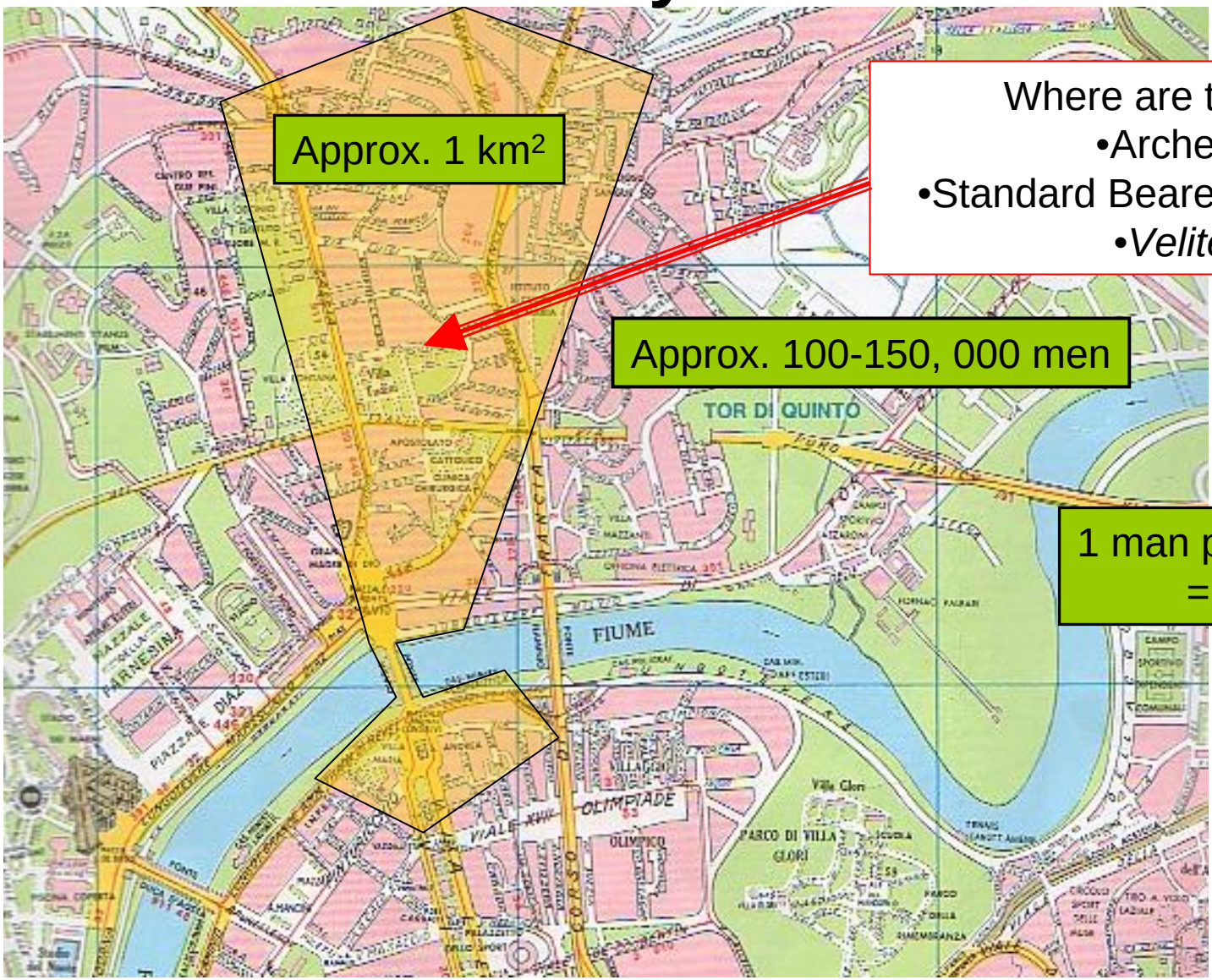

Where are the:
- Archers?
- Standard Bearers?
- *Velites*?

1 man per 10 m² =(3.16 m)²

Network is part of the Dynamical System

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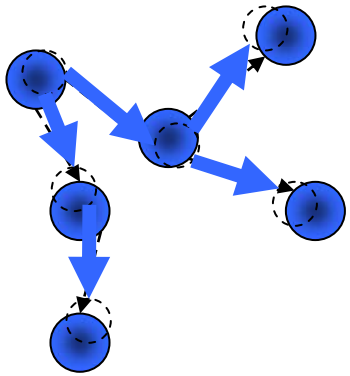

Hypothesis: <u>C2 links</u> are dynamical degrees of freedom which also carry entropy.

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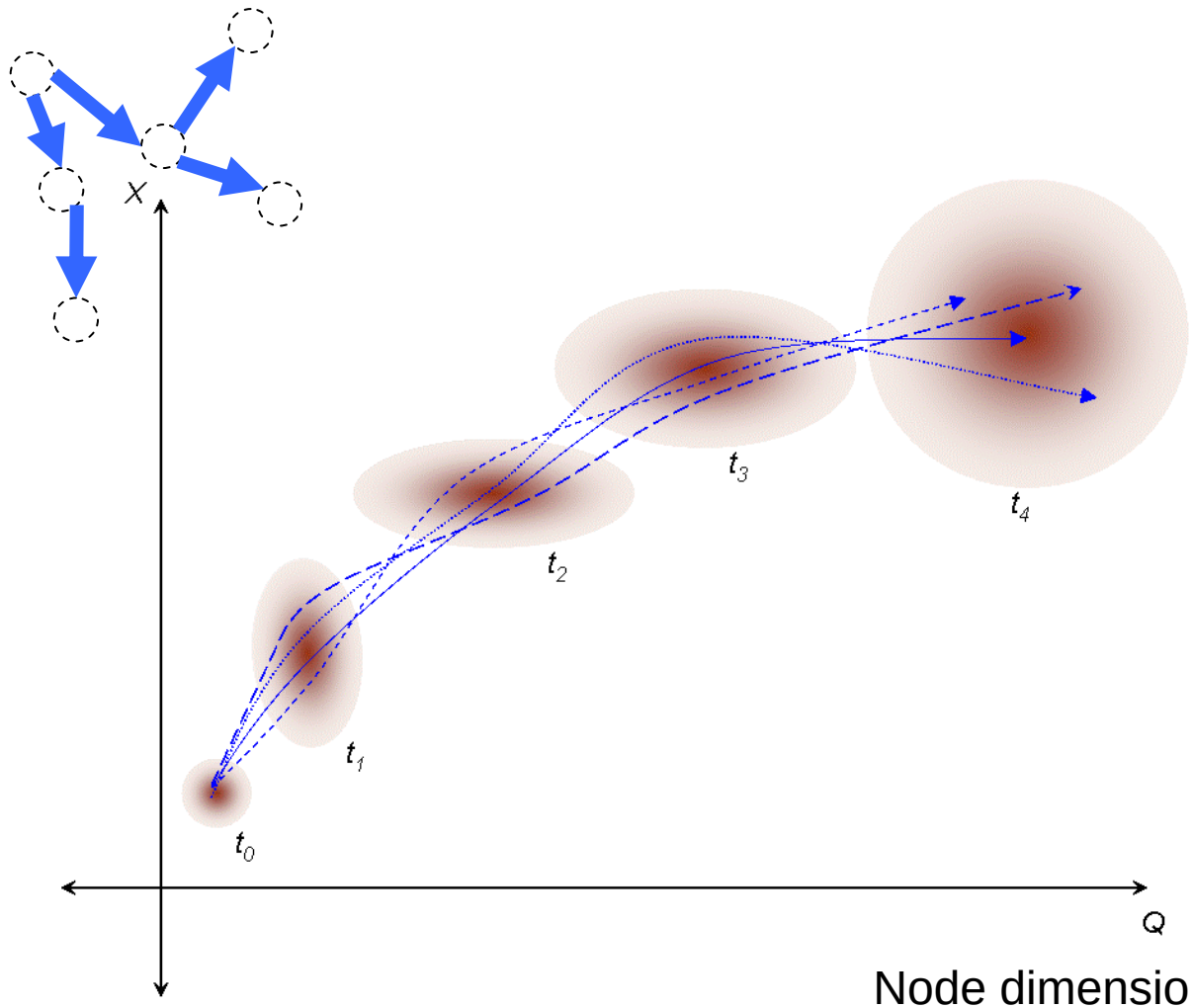
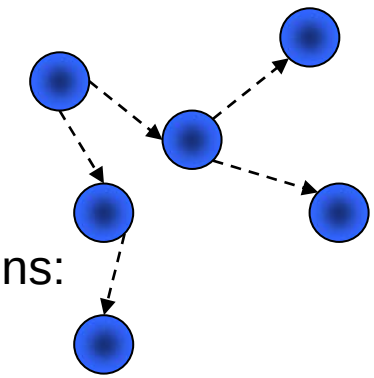
C2-Entropy and Phase Space

Link Dimensions:



Node dimensions:



The Battle of Jutland: 31 May-1 June, 1916

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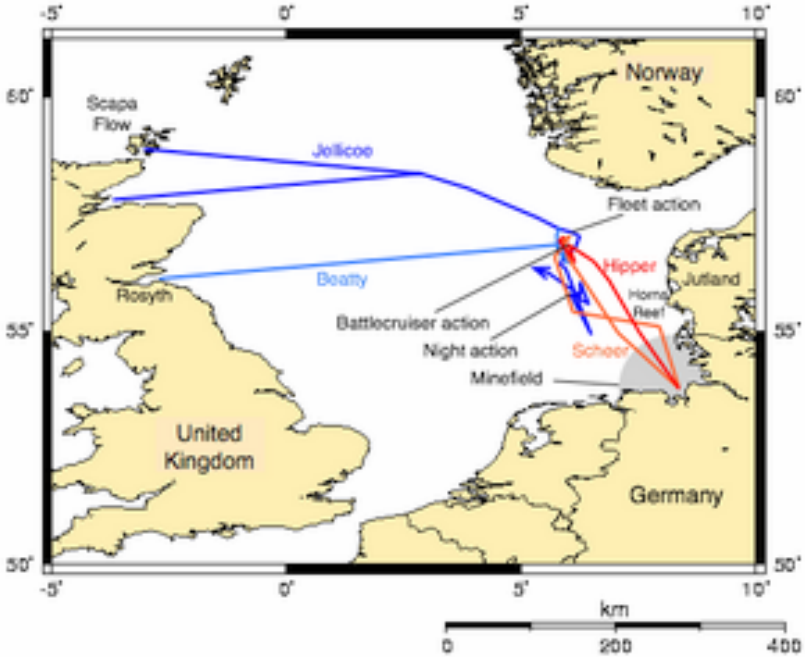

- British Royal Navy reliance on signalling for manoeuvre at sea.
- “flag-signal every 67 seconds” during daylight hrs.
- Parade-ground naval tactics: *disorder in space forbidden!*
- *Where did the disorder show itself?*

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Battlecruiser action: 16.55 31 May, 1916

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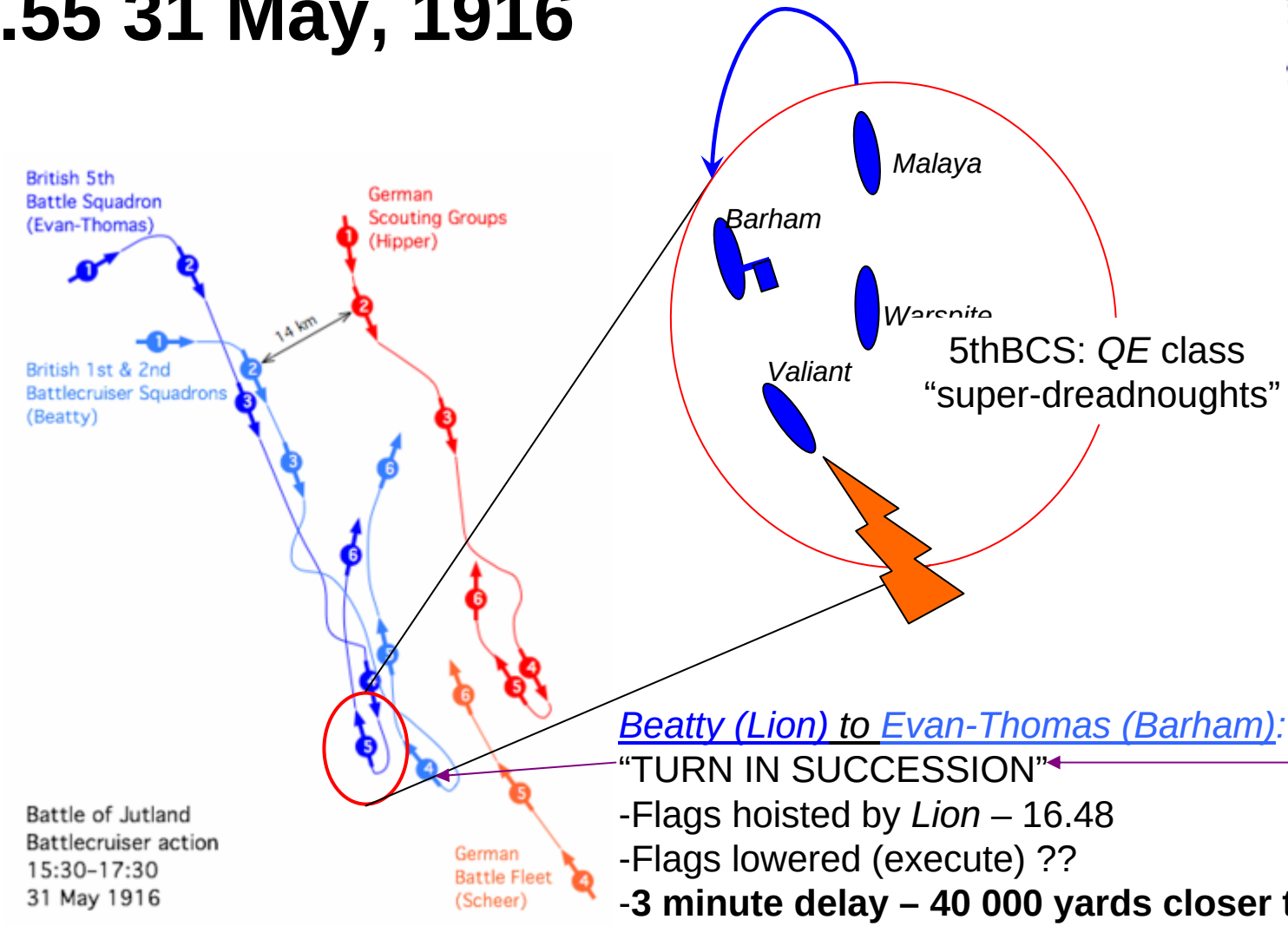
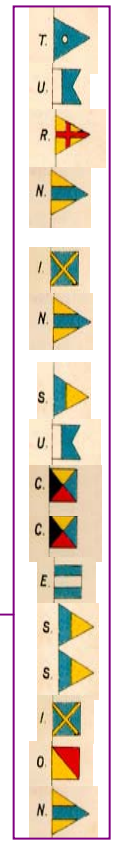


Beatty (Lion) to Evan-Thomas (Barham):
"TURN IN SUCCESSION"
-Flags hoisted by *Lion* – 16.48
-Flags lowered (execute) ??
-**3 minute delay – 40 000 yards closer to HSF!**



Ref: Andrew Gordon "Rules of the Game", 1996.

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Main Battle

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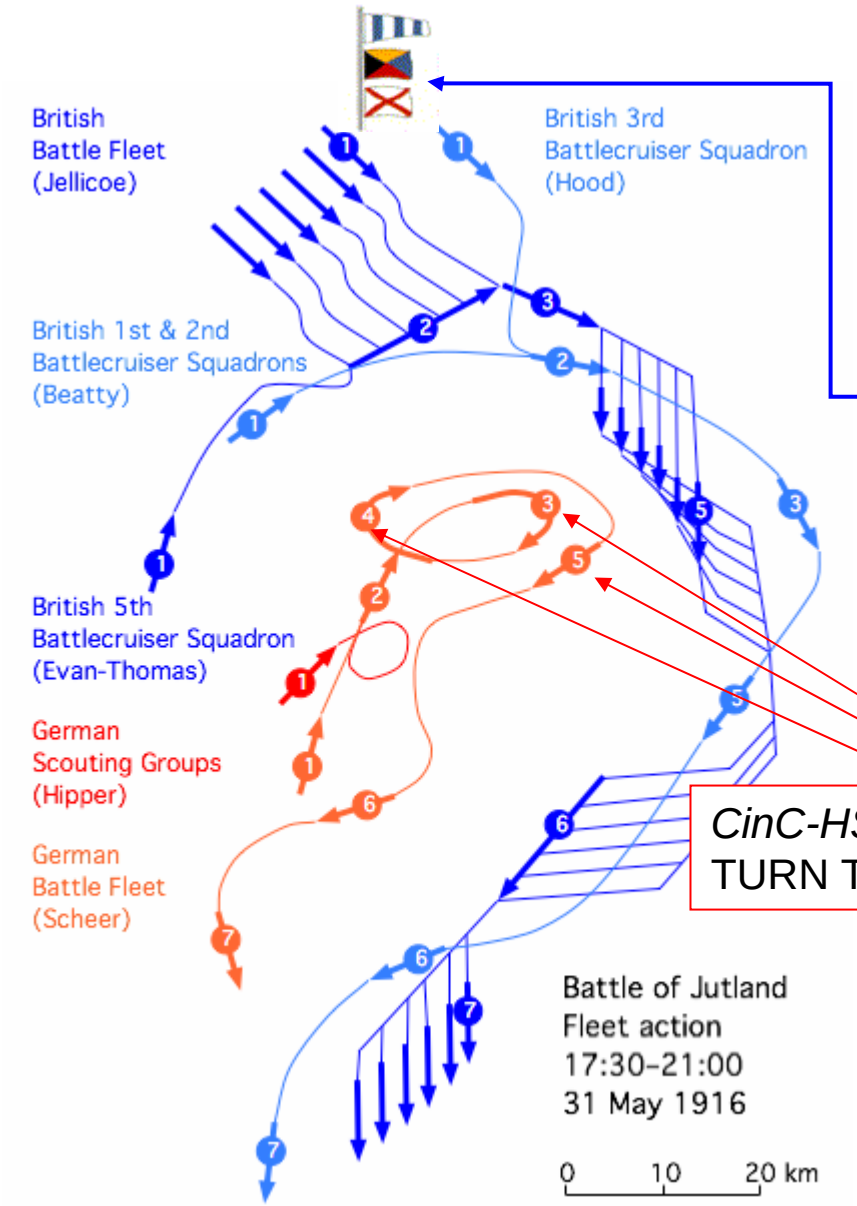
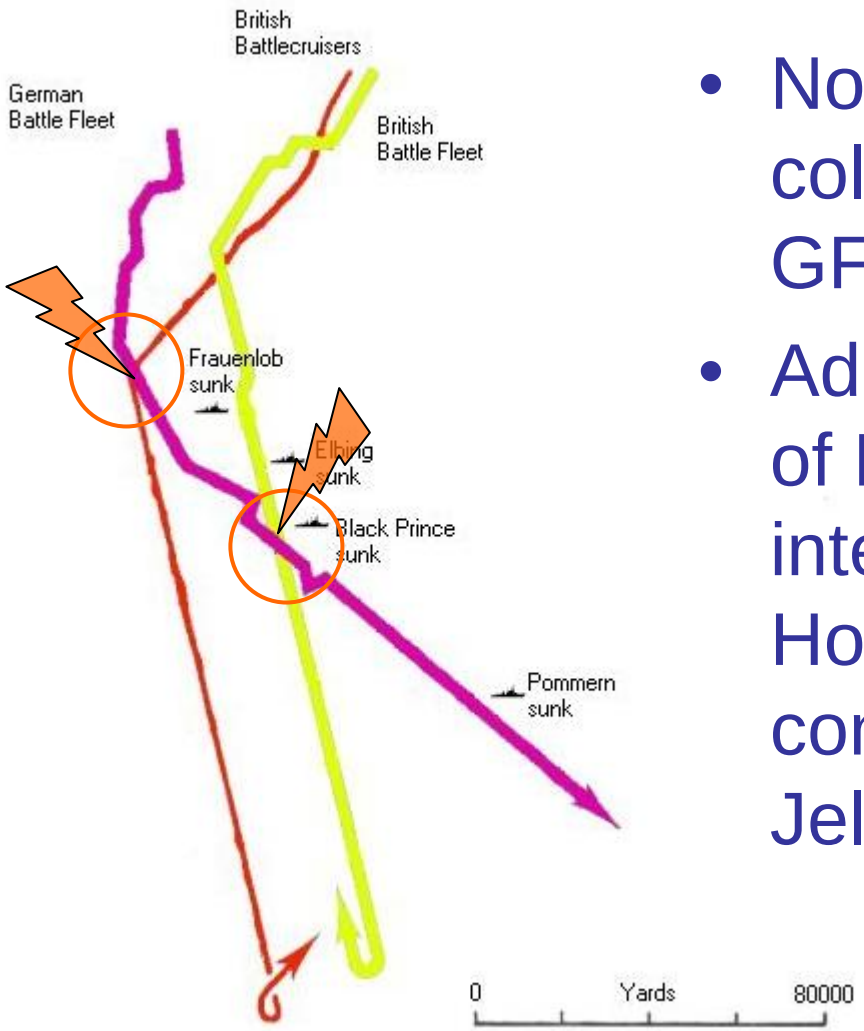


CinC-GF: "Equal-Speed-Charlie-London=
THE COLUMN NEAREST SOUTH-EAST-BY-EAST IS TO ALTER COURSE IN SUCCESSION TO THAT POINT OF THE COMPASS, THE REMAINING COLUMNS ALTERING COURSE LEADING SHIPS TOGETHER, THE REST IN SUCCESSION SO AS TO FORM ASTERN OF THAT COLUMN, MAINTAINING SPEED OF THE FLEET

CinC-HSF:
TURN TOGETHER 16 POINTS TO STARBOARD

Night Action



- No communication of collisions at rear of GF to Jellicoe!
- Admiralty intercepts of HSF radio with intention to head to Horn's Reef: not communicated to Jellicoe.

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Key British C2 “mistakes” at Jutland

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- Tactics depended upon spatial precision.
- Spatial movement *purely* determined by communication.
- Excessive communication permitted proliferation of errors which disrupted spatial movement.
- Tactical “defeat” (more ships and lives lost by British) though Strategic victory (High Seas Fleet no longer viable Fleet-in-Being).

- The British failed to maintain *latency* in C2 degrees of freedom:
  - high disorder in link space,
  - impediment to control spatial disposition of fleet.

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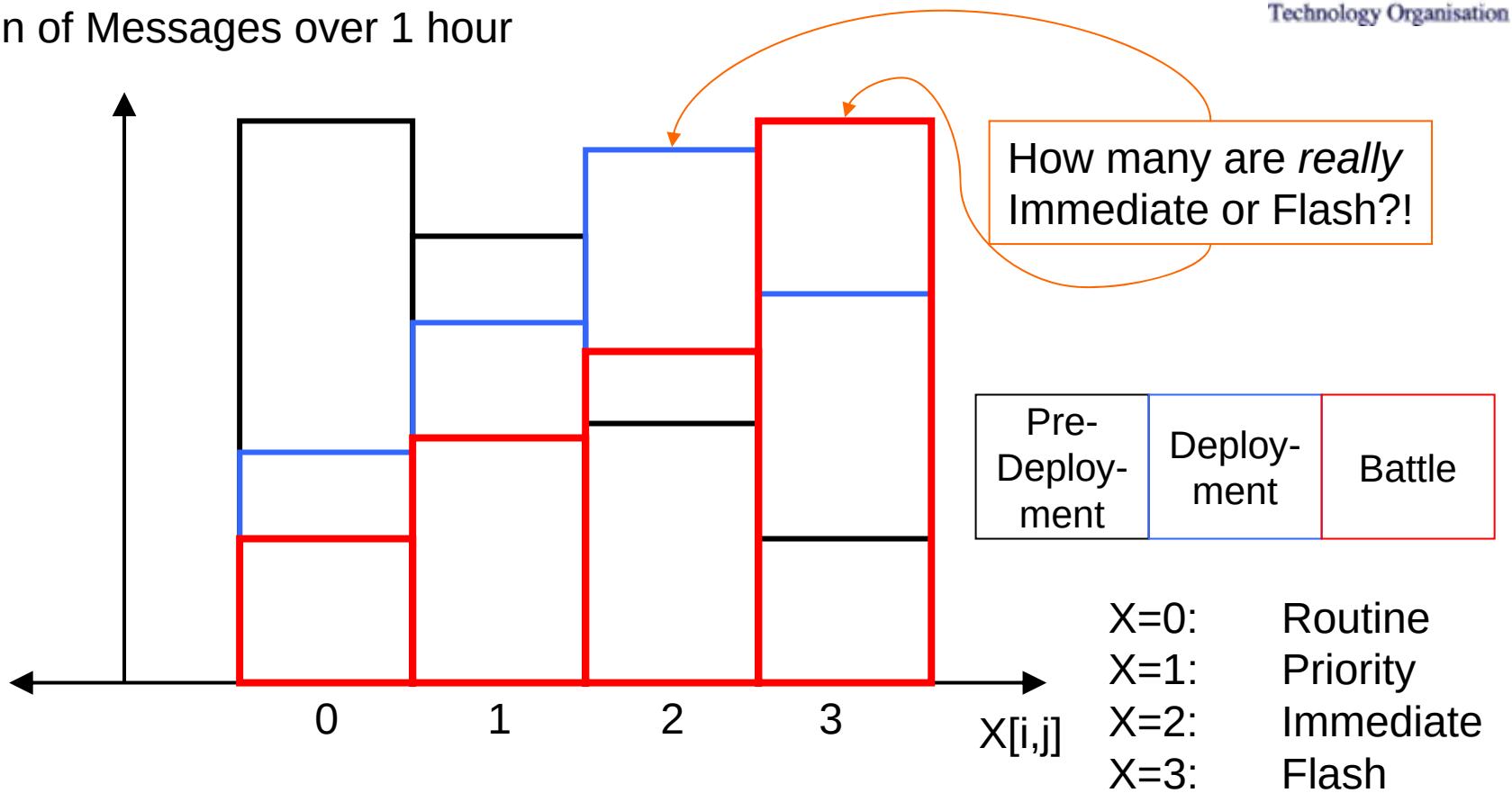
4. Implications for the Future Command and Control

Latency and Priority Creep

eg Gulf War I

Fraction of Messages over 1 hour



System evolves in C2-link space

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C2-Entropy and Mission Command

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- "… the **freedom** granted **junior commanders** to select their own way to the objective in accordance with the situation on the spot, **thus cutting down the amount of data processing required**; and the willingness of **superior headquarters to refrain from ordering** about their subordinates' subordinates – all these are indispensable elements of what the Germans, following Scharnhorst and Moltke, call *Auftragstaktik*, or mission-oriented command system."

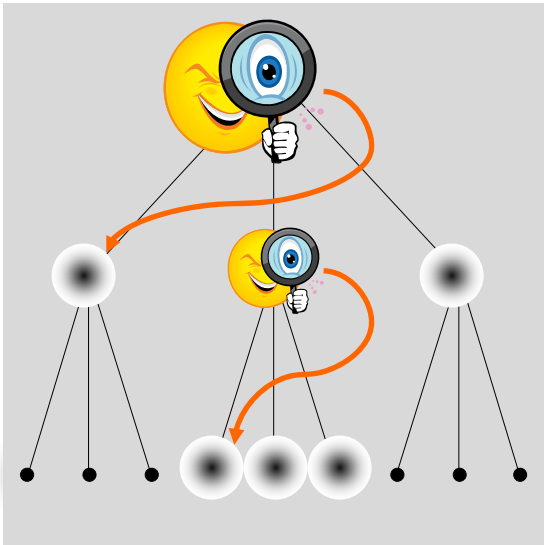
  Martin van Creveld, *Command in War*.

- Multi-level C2 in Complex Endeavours: highest commanders/controllers will be perceive highest entropy from tactical level.

- Mission Command decouples tiers.

- Entropy flow from bottom to top is minimised.

- Supports Adaptive Mission Command: as operation evolves increase in degree of Mission Command (Stewart, ICCRTS 2006).



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Lessons for NCW

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- Technologically enhanced C2: *Vast numbers of degrees of freedom*.
- Disorder is a necessary evil.

- *How to "deal with it":*
  - structured use of C2 degrees of freedom,
  - channel appropriately between nodes and links,
  - Maintain capacity to *surge* (latency) in those degrees of freedom.

- **The C2-Entropy Concept:**

  - ***C2-Entropy is a construct to manage disorder in a C2-system by channelling between node and link degrees of freedom in order to make the system flexible/adaptable.***

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5. Supplementary Material

ANZAC withdrawal: 19/20 December 1915

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- Withdrawal of Australian and NZ forces from Turkey over 2 nights without enemy noticing.
- Effective plan communicated in advance.
- Classic retreat strategy – strengthen front, hollow out rear, rearguard commander.
- Strong active C2-links with *minimal communication*!
- Good C2-Entropy management.

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C2:
Common Intent – Coordinated Action

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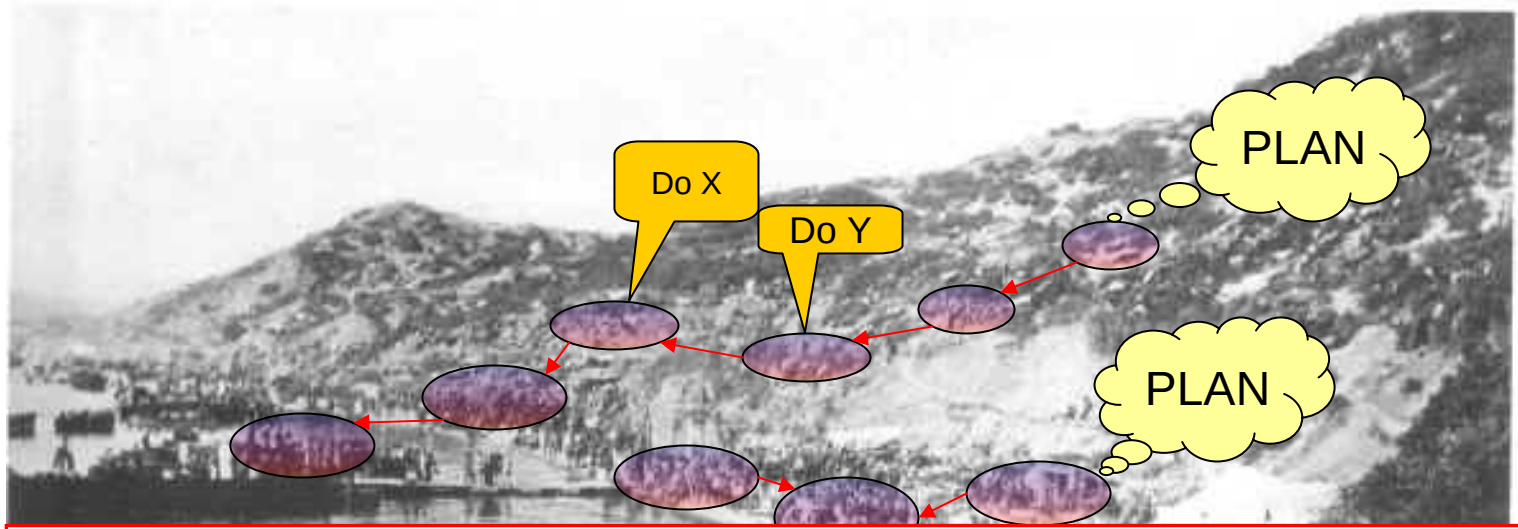

A shared, well understood plan meant:

•minimal communication,

•disorder dispersed between spatial and link degrees of freedom,

•*latency in links* was maintained.

Mathematical Formulation I

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C2-System *Node* State as a vector $q_{\mu,i}(t)$

Time evolution and influence of adjacent nodes

$$\dot{q}_{\mu,i}(t) = f[q_{\mu,i}(t)] + \sum_{\nu,j} G^{ij}_{\mu\nu}(t) h[q_{\nu,j}(t)]$$

Introduce noise *N* for "human factor": Langevin equation

$$\dot{q}_{\mu,i}(t) = f[q_{\mu,i}(t)] + \sum_{\nu,j} G^{ij}_{\mu\nu}(t) h[q_{\nu,j}(t)] + N_{\mu,i}(t)$$

Probability distribution

$$P[Q_{\mu,i}, t; Q^0_{\mu,i}, t_0]$$

Entropy is defined in terms of this distribution.

Associated Fokker-Planck equation:

$$\dot{P} = \frac{1}{2} \sum_{\nu,j} \frac{\partial}{\partial q_{\nu,j}} \left[\Omega \frac{\partial}{\partial q_{\nu,j}} P + F[Q_{\mu,i}] P \right]$$

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Mathematical Formulation II

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Initial State

$$P[Q,t;Q^0,t_0] = \delta[Q - Q^0]$$

Path Integral Formulation

$$P[Q,t;Q_0,t_0] = \int_{q(t_0)=Q_0}^{q(t)=Q} [dq] \exp\left(-S[q]/\Omega\right)$$

Introduce auxiliary "link" degrees of freedom $X_{\mu\nu,ij}(t)$

This is a term in *S:*

via Hubbard-Stratonovich transformation:

$$\exp\left[\sum_{a,b} \tfrac{1}{2} Z_i (A)_{ij} Z_j\right] = (2\pi)^{-n} (\det A)^{-1/2} \int \prod_i dX_i \exp\left[-\sum_{i,j} \tfrac{1}{2} X_i (A^{-1})_{ij} X_j + \sum_i Z_i X_i\right]$$

This introduces new terms in the action functional describing impact of link variables on node evolution and corresponding expansion or contraction of probability distribution and entropy.

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Path Integral illustration

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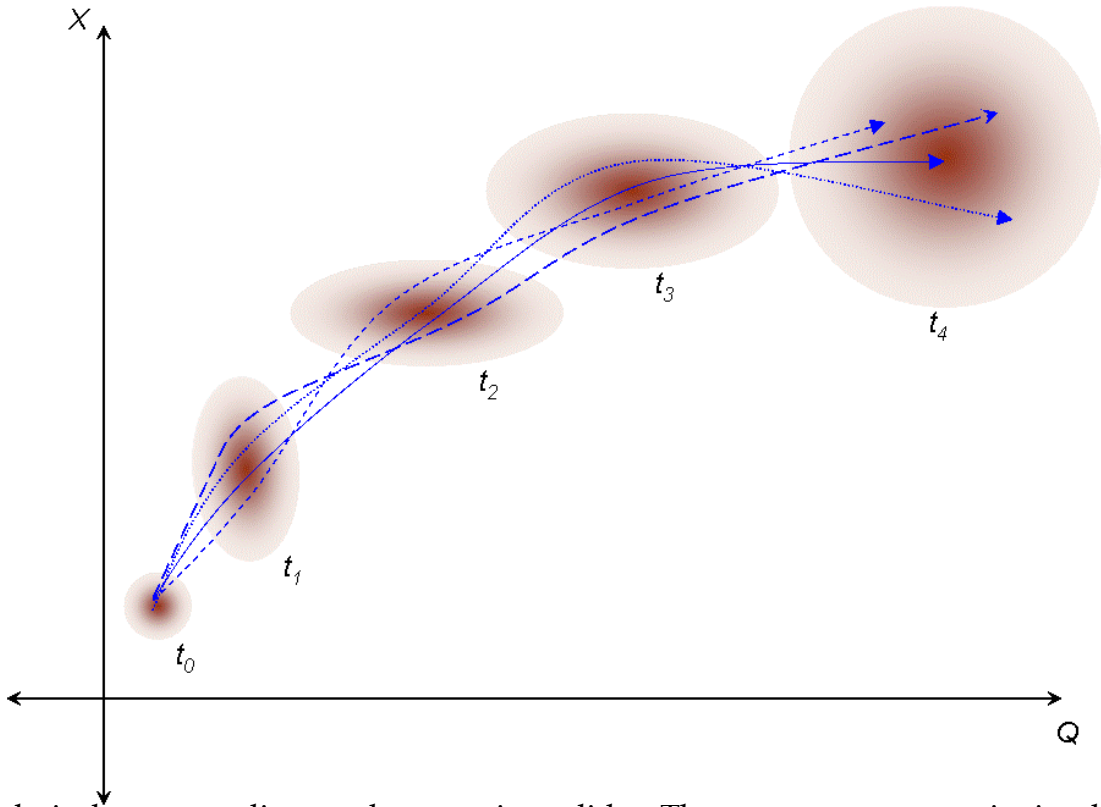

Illustration of the technical concepts discussed on previous slides. The system state space is simplified down to two variables, (for example, node and link degrees of freedom, respectively). The system state, a point, is smeared by stochastic influences into a region limiting the precision with which an observer can identify the precise system state. The initial state is well-defined at time t_0. The probability distribution evolves out of equilibrium, distorting in shape, as determined by the Fokker-Planck equation, through times t_1, t_2 and t_3 until it reaches equilibrium at time t_4. No further change occurs at the macroscopic level. Equilibrium is manifest in the uniformity of the final distribution. The path integral solution to the Fokker-Planck equation is illustrated through the blue trajectories. Each trajectory represents a possible system history from t_0 to t_4. The paths dominating the path integral solution are those which pass through the densest part of the probability cloud. The solid line represents the deterministic path for the system in the absence of noise.