Towards Flexible, Distributed Autonomy

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PURDUE ENGINEERING
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GROUPER Research Priorities

- *Group Performance Environments Research*
- How People Get, Share, and Use Information… Well
  - Aspects of Human-Computer Interaction and Interface Design
  - Distributed Expertise and Knowledge Sharing
  - Design and Implementation of Information Technology in Organizations
  - Task Coordination and Performance in Critical, Event-Driven Environments

Systems Engineering Design Issues

- System Definition
  - What problems are you addressing?
- Components
  - What features are important to you?
- Flows and Interactions
  - How does stuff get from one "place" to another?
- Performance Criteria
  - How do you know when you've improved anything?

Multidisciplinary Project and Event Response Teams

- Fundamental characteristics comparable across many environments
- Work is completed by teams to:
  - Share the workload
  - Share expertise (cross-functional)
- Work is often complex and highly integrated with other tasks - coordination crucial to quality and efficiency of product
  - Quality and timeliness!

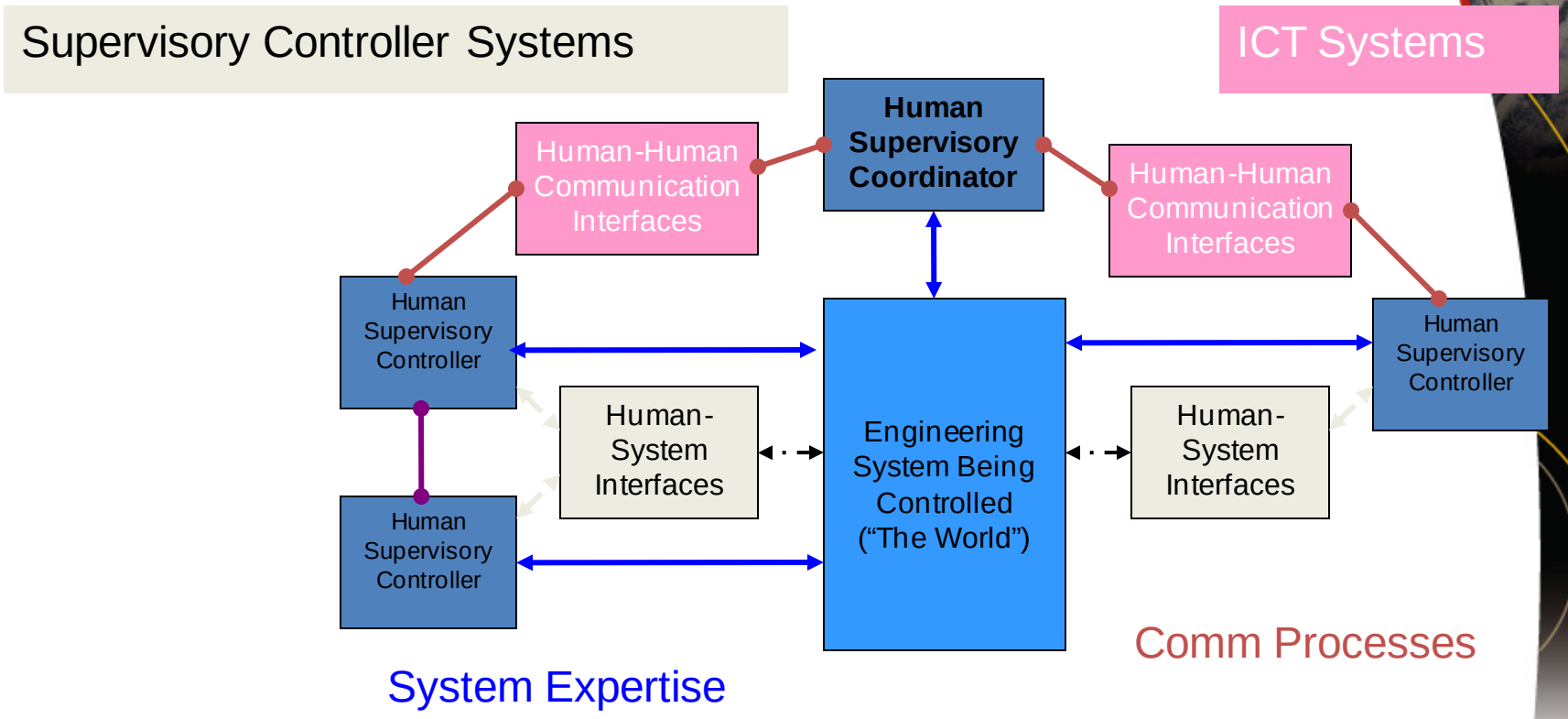
Complex Expert Teams as Systems

- Components with Differing Functions
- Interactions of Information Technology, Human Expertise, and Task Context
- Linking Reference Information to Operational Experience via Context and Experience
- Problem Solving Approach to Improving Operational Performance

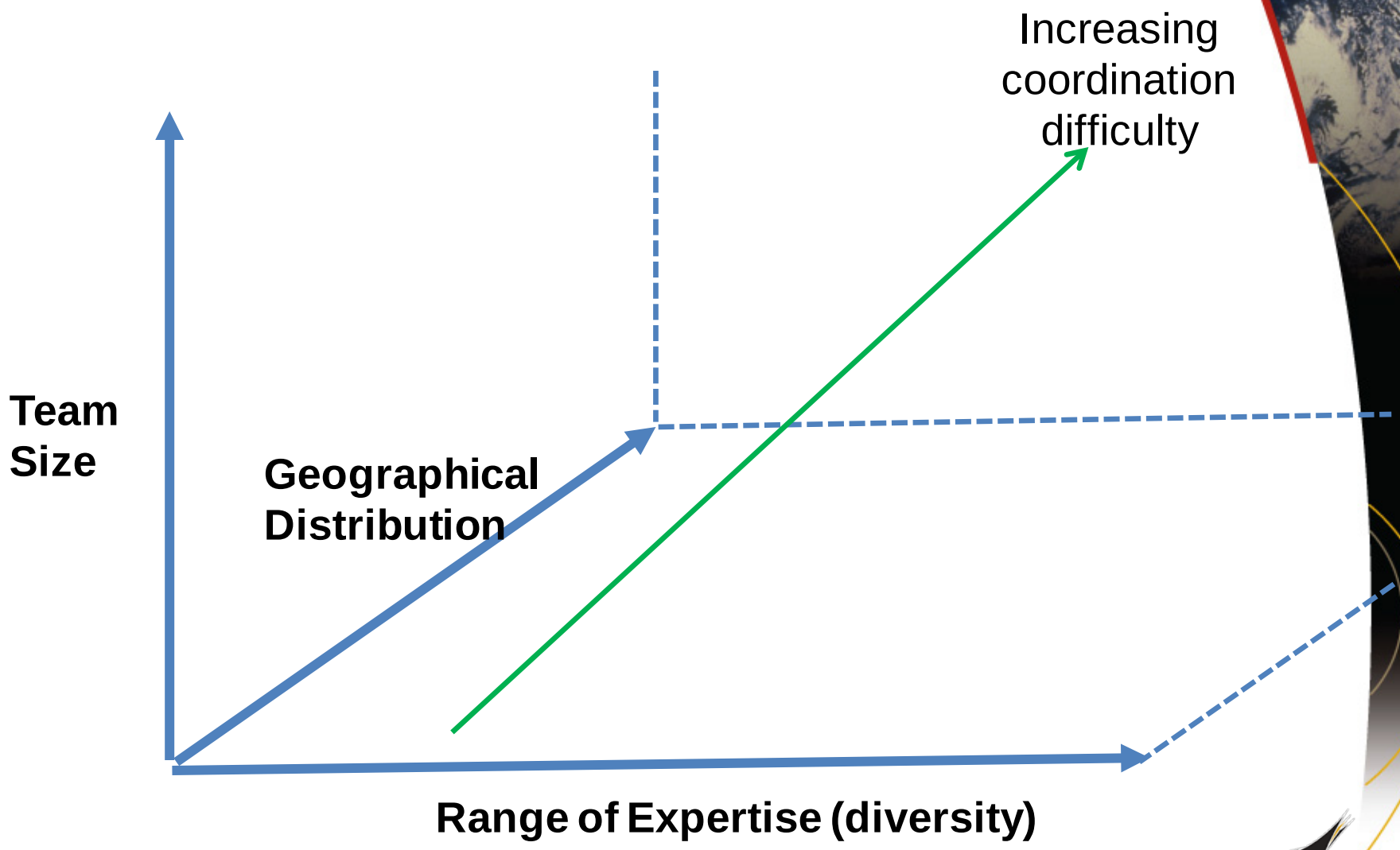
Three Challenging Ideas Regarding Information

- ***Data is not Information is not Knowledge is not Wisdom***
  - Bits are a measure of data, not of information or knowledge
- Information is Concentrations and Coupling, not Just Packets
- Information Needs Context and Reference to Events
- Information Has Timing Value

Distributed Supervisory Coordination (DSC) Model



Team Management

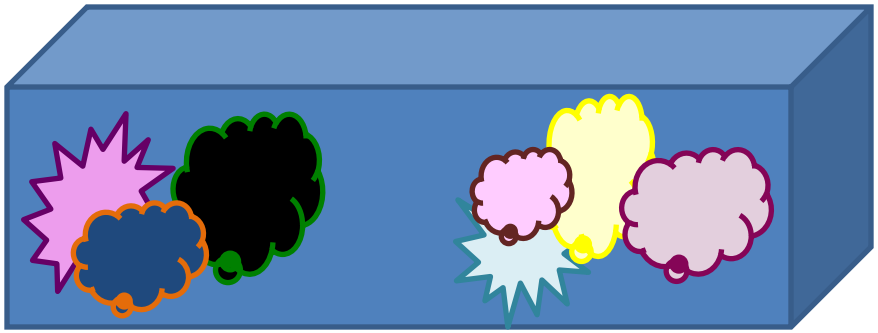


Impacts of Expertise on Coordinated Response

- Expertise Coordination in Distributed Settings among "Intelligent" Agents
  - Systems engineering approaches
  - Analysis of dynamics, flows, sources
  - Appropriate autonomy improves system robustness
- These concepts can be valuable for improving alignment in engineering teams
- Goal is to provide systematic analysis of the knowledge and expertise boundaries

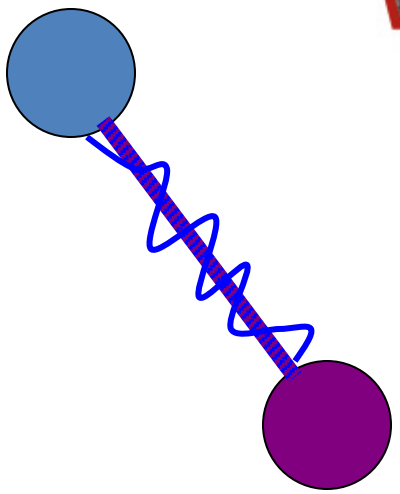
Managing Knowledge Clusters

- Effective coordination of experts represents an ongoing organizational challenge
- Expertise can function like the inertia of a physical object…
  - Thus, networks of experts are a set of "knowledge clusters" of varying size and density, occupying various regions of expertise



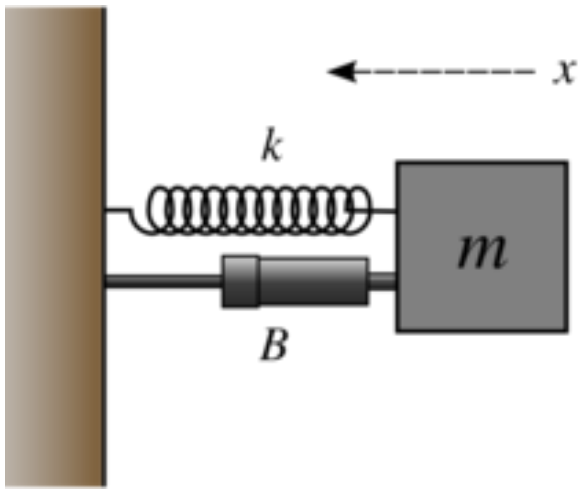
Information Alignment as Coupling

- Effective Transfer from Entity to Entity
  - Flows without loss or entries of noise
  - Linking clusters across domains in task context
- Timing Coordination
  - Appropriate recognition of scale, detail vs goal, in operational time
  - Decision and task value depends on "right information in time"
  - Flow velocity compared to material velocity



From Equations to Teams

- General Feedback Controls / Differential Equation Models
  - Useful across multiple engineering disciplines
  - ***Describes energy flow behavior, costs, and benefits***
  - Elegant use of few parameters
- Could this work for team coordination?



http://en.wikipedia.org/wiki/Damping

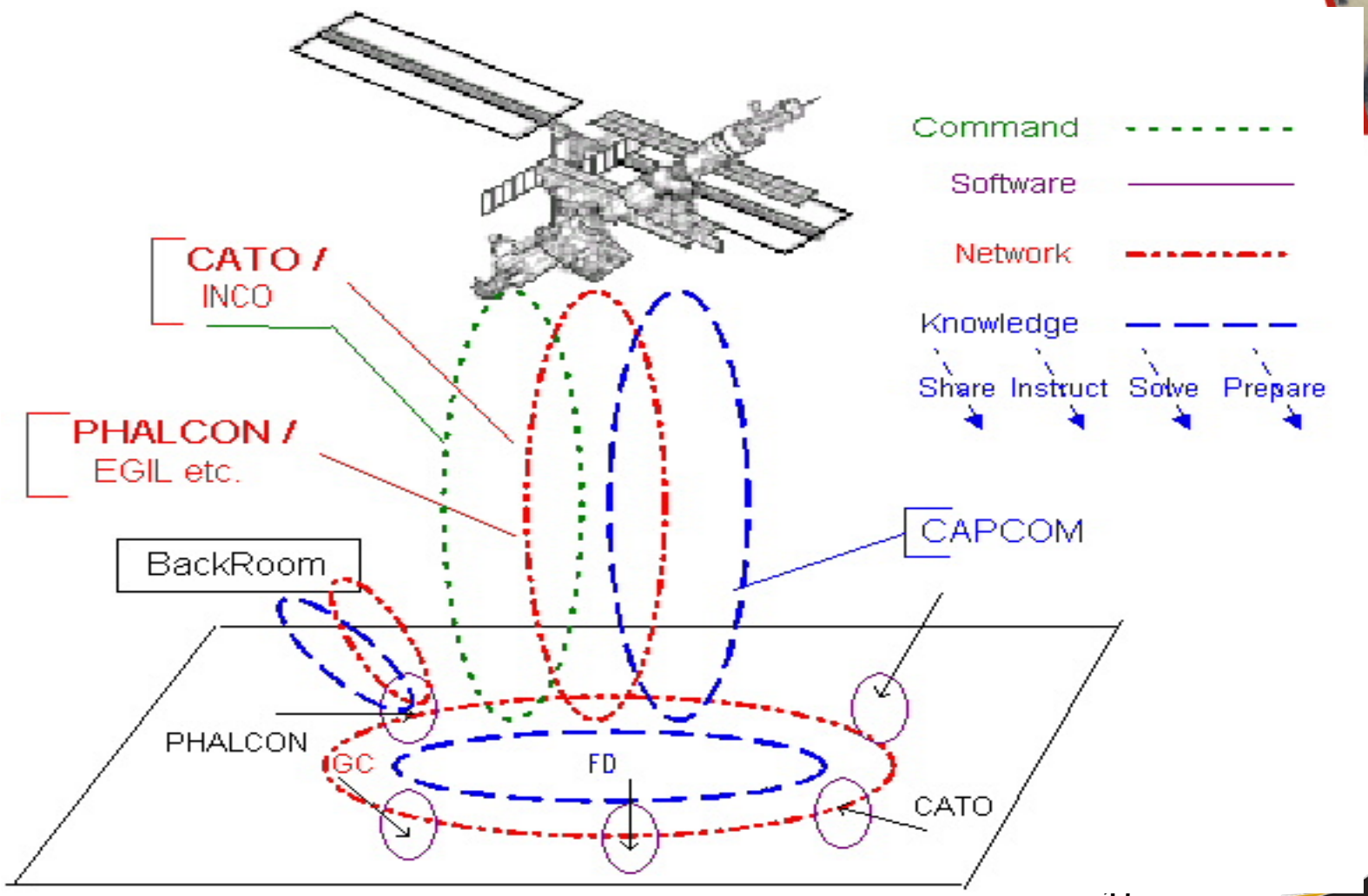
Expertise Coordination

- Team members must understand not only their own domain of expertise, but also have an awareness of the domains of team members with whom they interact
- A challenge to coordination involves how to explain one's expertise to others so that team members know what others know, and can provide information to them in a timely way
- *Dave Woods, "Margin of Maneuver"*

As-Is Mission Control Center (MCC)

- Primarily Ground-Heavy Mission Operations
  - 24/7 front room staffing
  - Reduced third shift
- Controller-Led Task Planning and Scheduling
  - More flexibility in ISS operations than STS
  - More flexibility with larger ISS crews
- Voice Communications with Data Support

As-is MCC: Multiple Loops



As-is MCC: STS side of ISS docking

Moving towards Future Mission Operations (FMO)

- Lessons from Crew Earth Observation (photography) and Other Crew Autonomy Experiences
- Operational Constraints for Future Missions
  - Cost, Staffing, Operational Complexity
- JPL Lunar C3I Architecture Studies
- Crew Autonomy Monitoring & Measurement Studies
- (Desert RATS Comm Testbeds: RT vs 2x/day)

An "Information Clutch" for Task Coordination

INFORMATION SYSTEMS

PRODUCTION TASK OUTPUTS

TEAM & ORGANIZATIONAL INTERACTIONS

Role of an Information Clutch

- Need to Understand Timing and Information Alignment of Tasks and Information in Distributed Environments
  - Handoffs of information across shifts, time zones
- Effects of Delays with Cyclic vs Absolute Deadlines
  - Can information be used again?
  - What is cost of old "stale" information in responding to dynamic requirements?
  - What can we learn from event to event?

Moving towards FMO: Concerns

- What Are Elements To Enhance Sharing?
  - Higher-order knowledge, not lower-order data
- Evolving Operational Paradigms?
  - Human crewmembers, increasingly capable automation
- Increase Operational Capacity, Efficiency, Flexibility?
  - Scaling less than linear in # of vehicles (cf. JPL)

Moving towards FMO: Concerns

- Knowledge Gap: No Experimental Variance
  - Population of human spaceflight MCC centers?
- Building FMO Prototypes
  - Simulations of events, *C3I flows*, ***architectures***?
- Team-Level Interactions among Controllers
  - → Simulation-based human factors
  - → Human factors-informed simulation

Distributed Autonomy Issues

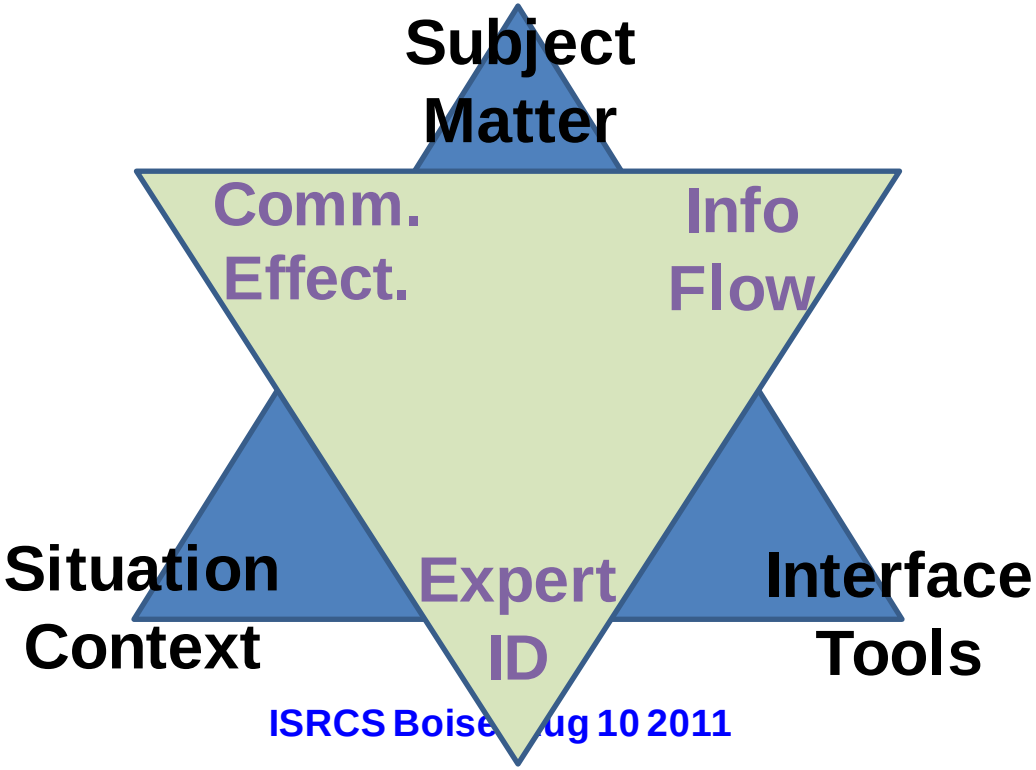
- Confusion of Terms, Disciplines, Perspectives
- Autonomy vs. Automation
  - Automation: execution of task through artificial system
  - Autonomy: independent reasoning, solving, tasking
- Sheridan's Levels of ~~Automation~~ (Autonomy)
  - Function allocation between humans and automation
  - Limited within supervisory control contexts

How Do Strategies and Tasks Change as Teams near Capacity?

- Acceleration, Reprioritization, Omission
  - Efficient use of information when time becomes significant constraint
- Changing Roles and Response Criteria
- Task Stabilization vs Completion
  - Picking which tasks to provide interim solutions
  - Strategic triaging of resources and constraints
- Effects of Effective Coordination Become More Pronounced with Challenges and Expertise

Recognizing Multiple Dimensions of Expertise

- Six dimensions of expertise used to more fully study the structure of expertise within a team and enable coordination between members



Distributed Autonomy Issues

- Basic Elements of Autonomy
  - From whom?
  - To do what?
- Examples
  - Rover entering auto sleep mode (independent robot)
  - EVA crew receiving modified instructions (reliant human)
- Dynamic Distributions of Autonomy
  - Where are functions allocated ***right now***?

Distributed Autonomy Issues

- Graded Conditions of Autonomy
  - No autonomy (receiving step by step instructions)
  - Veto ("I can't do that")
  - Operational Sequence (Right steps, right time)
  - Task Activity (Achieve goal best way determined)
  - Goal Determination (recreation, mission reconfig)
- Mission Profile and Events Affect Available Capability Margins

Past, Current, Future Applications

- Lunar Command, Control, Communications, and Information (C3I) Architecture Planning Model
  - Multiple lunar resources and sorties
  - Robotic assistants and distributed crew
  - Local, lunar, non-Earth, and integrated C3I
- Apollo-Style through Mars-Forward
  - Ranges of real-time (but asynchronous) comm
  - Planned and unplanned comm outage

Applications: Conferring Autonomy

- Four Levels, Based on Comm and Events
  - Immediate
  - Short-term
  - Tactical
  - Strategic
- Consider Factors of Bandwidth, Delay, Autonomy
  - Frequency of communication
  - Level of monitoring, replanning, self-awareness

Applications: Conferring Autonomy

- Immediate
  - Small task range and time of activity, "move-and-wait" (low autonomy, short delay)
- Short-term
  - Brief tasks, or few steps of larger tasks (sequence support, not "command paced")
- Tactical
  - Task and operational sequences can be modified
- Strategic
  - Goal prioritization, situation responsiveness

Conclusions

- Challenges of Understanding Distributed Expertise and Task Coordination
  - Dimensions of Expertise
  - Needs for Information Coordination and Sharing
    - Foraging
    - Knowledge Clusters
    - Metadata Flow
  - Teams, Tasks, Time in Dynamics Settings
- Understanding How Experts View the World
- Projects that Emphasize Real Constraints and Complexity

Thank You

- Questions?
- Contact: bscaldwell@purdue.edu
- Website: http://www.grouperlab.org

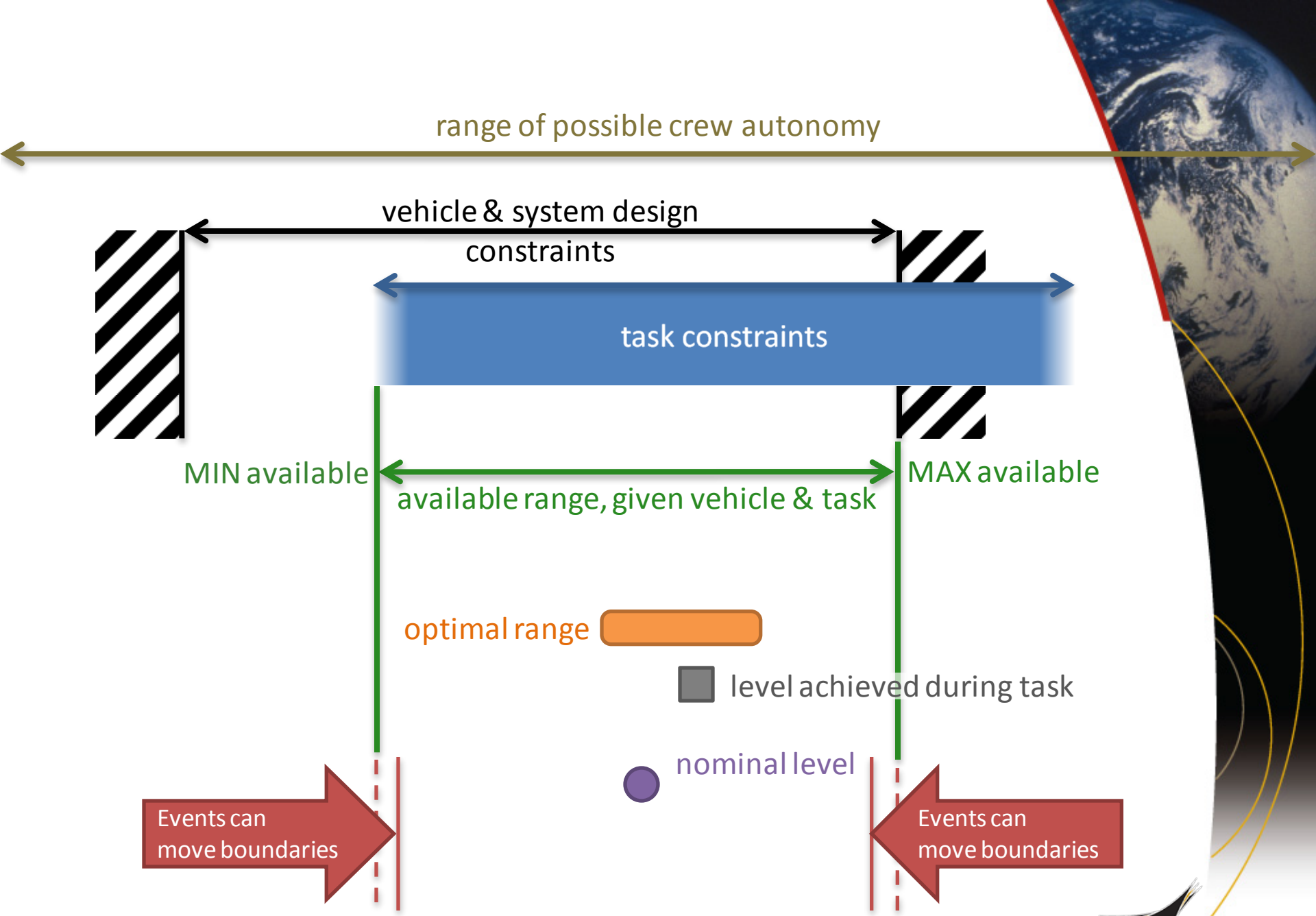
The sage never tries to store things up.
The more he gives away, the more he has.
The more he gives to others, the greater his abundance.
--*Lao Tsu*, Tao Te Ching, *81 (Feng / English trans.)*

Expertise, Information, Context

- Tai Ji Example
  - First lessons: too much, no linkages
  - Developing skills: more awareness internally and externally
  - Learner's path: new contexts, new combinations
- Role of Practice and Variety of Experience
- Need for Coordination
  - Too much communication interferes with task
  - Not enough communication encourages misunderstanding and potential confusion

Past, Current, Future Applications

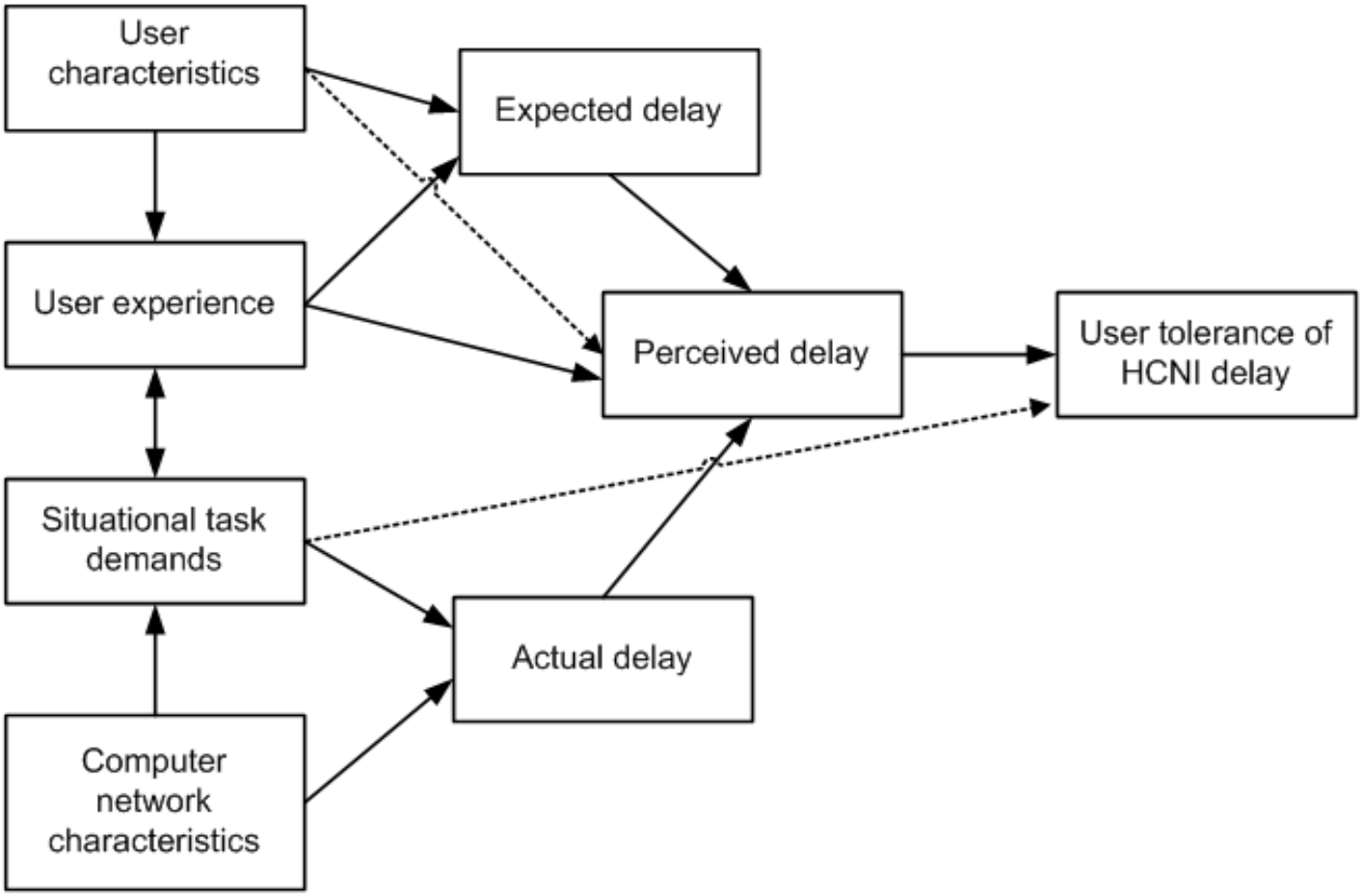
- Crew Autonomy Measures and Models
  - SBIR Phase I project (SA Technologies)
  - Autonomy impacts taxonomies
  - Real-time crew autonomy capabilities
- Critical Issues
  - Develop frameworks to evaluate scenarios
  - Implement operational models focused on crew and FMO


range of possible crew autonomy
vehicle & system design constraints
task constraints
MIN available
MAX available
available range, given vehicle & task
optimal range
level achieved during task
nominal level
Events can move boundaries
Events can move boundaries

(Some) Results of Wang Research

- Time Pressure is Not Just Absolute Time, But Affected by Network Performance, Expectation, and Task Factors
  - Experience of prior delays
  - Alternatives for task completion
- Understanding of "System as Evolving" Affects Models of System Performance
- Time Pressure as Ratio of Required to Available Time
  - T_r/T_a now used in other studies

Interaction of Delay Factors from Wang Research



Metadata and Knowledge Clusters

- Why is context metadata sharing among distributed experts important?
  - Much information and little time to process it.
  - Metadata can be used to effectively generate, retrieve, interpret, and communicate the meaningful information from all the *possible* useful information in a task setting.

Cooperation and Coordination among Knowledge Clusters

- Expertise often transcends specific knowledge domains
  - Associating non-explicit metadata
- Level of specific task focus
  - Common vocabulary to promote homogeneity
  - For instance, what do people understand when we talk of traffic management?

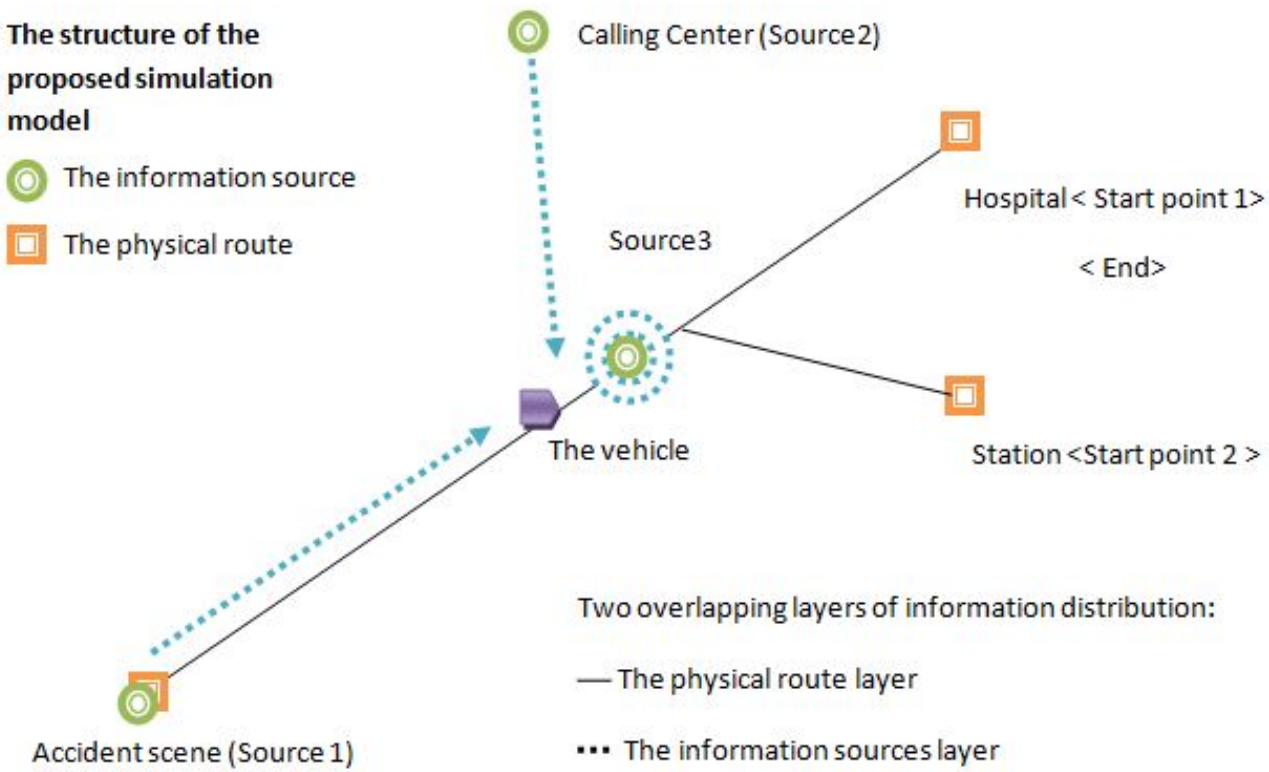
Example Project and Integration

- Liang Wang, MS student, Studying Mobile Emergency Response Teams
  - Emergency Medical Service (EMS) is a time sensitive area of healthcare delivery and management of social infrastructure.
  - The availability of information vs. the availability of time: EMS system is heavily dependent on time-critical decision making, the availability of information is of first priority.
  - Most Studies are focused on resource allocation, based on a steady state assumption, yet the real system is changing with time.

EMS Task Focus: Ambulance Response

- Accident or Illness: Patient or Witness Calls Emergency Number
  - Usually limited information, difficult communication
- Dispatch Service Contacts Ambulance
  - Research focus on optimal dispatch, task ends when ambulance called
- Ambulance Responds: Travel to Site, Then to Hospital
  - Need to navigate traffic quickly
  - Preparation for only partially known situation

Coordination Challenge: Integrating Event, Traffic, and Urgency Information



Possible Approach: Information tracking with the concentration model

- $IC_j = P_d B_d X_d(t,\mathbf{r}) + P_s B_s X_s(\mathbf{t},r) + P_{tr} B_{tr} X_{tr}(\mathbf{t},r) + P_g B_g X_g(\mathbf{t},\mathbf{r(t)})$
- Physical layer and Information layer
- Simulation methods
  - Kernel density estimation for dual layer information concentrations and clusters
  - Dynamics of kernels and cost of delay (different paper)
- An alternative indicator for route navigation: maximizing the concentration while minimizing time to collect concentration

Summary of Project Example and Other GROUPER Projects

- Existing Research Focuses on General Expectation, Not Real-Time Task Dynamics
- Complexity of Expert Understanding, Balancing Demands for Excellent Performance
- Real-Time Task Coordination Distinct from Scheduling or Optimization
- Need to Understand How Real Experts Get, Share, Use Information