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BAYESIAN ANALYSIS OF MULTI-SCALE TEAM STRUCTURE (BAMS)

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Proposed Work:

We will develop a new and general framework for **characterizing the multiscale structure of teams** as they adapt and change in response to a dynamic problem space, directly addressing TA1. Two key areas where our work will advance the state of the art are:

1) Explicit quantification of multiscale team structure, where individuals can be associated to a number of sub-groups varying in size (e.g. from pairs to groups to the whole team), and wherein this structure can be organized in a variety of ways (from military hierarchy to an agile scrum).
2) Explicit accounting of environmental stochasticity (including both endogenous environmental perturbations as well as possible strategic moves by an adversarial team) and team dynamism where a team's composition and size change.

We will achieve these goals using a new approach for quantifying the dynamic structure of agile hybrid Human-AI teams: **Bayesian Analysis of Multi-scale team Structure (BAMS)**.

BAMS objectively characterizes multiscale team structure using a new data analytic approach -- wavelet maps. That is, for any given graph describing the interactions/relations between agents comprising a team -- for example a weighted synergy graph -- wavelet maps provides a local coordinate system for capturing efficacy in collaboration at various scales, for example between a few agents interacting directly, or over a subgroup tasked with a specific sub-problem, or the whole team. Wavelet maps identify the most important scales of interaction for each agent in a team, providing an objective multiscale decomposition of team structure/organization. The problem/goal set for a given team is often hierarchical in nature (almost any problem subdivides) and using wavelet maps BAMS can identify subgroups, potentially overlapping, that form functional modules of agents which can be matched to subproblems allowing the team to achieve subgoals in parallel.

BAMS deals with a changing problem space by formulating optimal subgroups in terms of graph spectral structure. Rather than utilizing a fixed graph whose edges represent pairwise synergies we propose that the problem space can be reduced to a partially ordered sequence of tasks, and that each agent in a team has a measure of efficacy in addressing each task. The edges of the graph indicate the factor by which two agents increase/decrease their efficacy when working together. The goal is not to find the optimal subset of agents to address the problem, but to allocate each agent's resources (time, energy, etc.) among all its potential collaborations in a way that maximizes their collective impact, measured through their wavelet map coordinates. In doing so, BAMS will be able to deal with changing problems; for example in competitive games agents may need to adopt locally suboptimal roles (e.g. in soccer sometimes a striker has to play goalie because someone has been sent off) that globally (i.e. over the whole team) form an optimal solution.

BAMS encodes variability in the environment, goals, tasks, team interactions, roles, and individual characteristics by embedding wavelet maps in a Bayesian hierarchical framework. Putting prior distributions on environmental factors, edge weights, and node efficacies, we may estimate the probability that a given team structure/protocol is successful in achieving its (sub)goal. Hence, the choice of a certain team structure has an associated risk derived from the environmental and agent-based noise. Quantifying uncertainty in this manner allows us to define different team structures based on their risk, ranging from those that are highly specialized to a particular task but may be vulnerable to small deviations in parameters (a high risk / high reward team structure) to those that would be suboptimal in a deterministic setting but are robust to variations in the environment or team (a low risk / low reward structure). These trade-offs are well known in finance through modern portfolio theory and in ecology, where generalist and specialist species compete.

BAMS will be used to identify minimal models for weaving an intelligent AI fabric. Given a collection of human team members and a set of goals, the task of assigning complementary AI agents to the team is easily defined within the BAMS framework. By allowing each AI node in the network to have skills spanning all of its potential assignments, the allocation of its energy to a given role (i.e. addressing a particular task) when optimizing team impact will define what role that AI agent fulfills. *This allows the AI agents' functional role and position in the team to be determined dynamically by the problem state.* Furthermore, while BAMS provides a general framework, given knowledge about the source and types of (environmental) noise and the roles that AI members can take (e.g. modulating communications, or individual human-agent effectiveness) it can be specified to a minimal model for a given system. These minimal models will reveal "rules of thumb" for weaving an intelligent AI fabric for hybrid teams, where AI agents modulate the interaction graph, and hence the multiscale organization identified by wavelet maps.

Impacts on TA2: Problem Solving:

One vital aspect of TA2 that will be improved by the use of BAMS is the incorporation of uncertainty in the solution strategy. In situations of environmental uncertainty, not only will a generalist team structure be more conservative, but AI collective problem solving approaches will need to be resilient to noise. As in economic modeling, the higher the uncertainty the more agents must discount their projection of the future state of the system. For example, in a high-noise environment planning for shorter-term goals should be encouraged, as agents cannot have great confidence in the state their actions will lead to. Indeed, within the BAMS framework, team structuring decisions can be made based on a chosen or evolving risk preference. For example, in risk averse situations, high risk / high reward team structures can be avoided (e.g. at the start of a competitive game), but in situations where risk seeking behaviors are desired (e.g. at the end of a game when you are losing), high risk team structures can be identified and adopted.

A DARPA YFA Foundation:

The proposed work described above rests on mathematical and computational advances made under an ongoing DARPA YFA. Specifically, my YFA team has advanced new graph Laplacian spectral methods for characterizing the multiscale structure of complex and dynamic systems. One such approach uses *diffusion maps* (1) to classify and predict changes in collective behavior in biology. This initial YFA work utilizes the eigenspectrum of sequentially calculated graph Laplacians (see attached paper in review at PNAS: 2). A major limit to this approach is the lack of quantitative determination of the important network scales and the inability to localize this information. To overcome these limitations, we have advanced a new method based on graph Laplacian wavelet functions that provides a multiscale decomposition of network structure, identifying the most important scales, and does so locally at each vertex. These *proto wavelet maps* have helped us classify multiscale changes in human mobility (attached paper in prep for PNAS; 3). Wavelet maps of evolving networks has also motivated us to study leaders and followers in biological collectives (see attached whitepaper; 4).

References

(1) Coifman, R.R. and Lafon, S., 2006. Diffusion maps. Applied and computational harmonic analysis, 21(1), pp.5-30.

(2) Titus M., Hagstrom G., Gelbaum Z., Watson J.R., Manifold Learning of Collective Behavior in Nature. Submitted to PNAS.

(3) Watson J.R., Gelbaum G., Titus M., Zoch G., Wrathall D. Manifold Learning of the Dominant Modes of Human Mobility. To be submitted to PNAS.

(4) Gelbaum G., Titus M., Watson J.R. Multiscale Decomposition of Collective Organization in Nature and Society. Technical White-paper.