Report on the Formation of a New Entity in the Areas of Complex and Socio-technical Systems, Information and Decision Systems, and Statistics

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Executive Summary

1. The Opportunity

Technological advancements including smart and embedded sensors, high-speed communication, social networking, and real-time decision capabilities have resulted in the emergence of large scale, heterogeneous, interconnected systems. Analyzing and modeling such complex systems remains a major challenge for researchers and practitioners. Their design and control/regulation are even more challenging, yet they must satisfy critical societal needs.

Systems directly impacting our society often involve the interactions of three heterogeneous features: 1) an engineered or natural physical system, 2) social behavior of people interacting with the system, and 3) institutional behavior of organized units such as regulators and markets governing the system. Traditionally, such systems (often referred to as socio-technical systems) have been analyzed and (when possible) designed with each of these features in isolation. This has resulted in suboptimal and fragile interconnections. The technological advancements, combined with increased computational capabilities, and the ability to collect vast amounts of detailed data give us a new opportunity to holistically, systematically, and scientifically address the broad challenges facing these complex systems. Examples of such systems include, but are not limited to, energy, transportation, finance, healthcare, manufacturing, and social networks. The new Entity intends to have a substantial impact on these critical societal systems.

Mission

We propose the formation of a new Entity at MIT to establish, coordinate and lead research and educational programs with the following mission:

- *Create a research and educational environment that enables analyzing, predicting, designing and controlling complex societal and technical systems.*
- *Create an Institute-wide focal point for advancing MIT's research and educational programs related to 21st century statistics.*

Research in the entity will address overarching challenges including modeling and prediction of system behavior and performance, systems design and architecture, and issues including social welfare and sustainability, and resilience and systemic risk. Research will connect closely with domain expertise to understand the challenges and opportunities in complex systems of interest. Educational and research methodologies will be anchored in the cross-disciplinary fields of statistics, information and decision sciences, and human and institutional behavior.

Value Proposition

As MIT continues to position itself as the hub for innovations that impact societies at large, it is becoming evident that the formation of this new Entity is critical to maintaining MIT's competitive edge in the broad field of mathematical, behavioral and empirical sciences and its impact on complex societal problems. The new Entity will have an impact on research and education in the following way.

a) Launch an Institute-wide effort in 21st century statistics and data science as well as consolidate this new effort with existing expertise in information and decision sciences.
b) Create a unique research environment at MIT that bridges domain knowledge with advanced analytical expertise to understand the challenges and exploit the opportunities of complex systems (including socio-technical systems).
c) Create unique and attractive educational programs to provide preparation for research in this field. The outcome of such programs is a new generation of students with expertise across disciplinary domains in the broad field of mathematical, behavioral, and empirical sciences applied to the study of complex systems. This expertise will position them to be leaders in industrial, academic, and governmental institutions.
d) Provide a hub for expertise in the cross-disciplinary fields of statistics, information and decision sciences, and human and institutional behavior. This hub will lay the foundation for attracting the best faculty complement to support this effort.

2. Education and Academic Programs

The proposed Entity embraces the collision and synthesis of ideas and methods from analytical disciplines including statistics, stochastic modeling, information theory and inference, systems and control theory, optimization, economics, human and social behavior, and network science. These disciplines are relevant for understanding complex systems, addressing overarching challenges (including sustainability and systemic risk), and for presenting design principles and architectures that enable those systems' quantification, management and provide a basis for the formulation of policy. Each one of the above fields, in its traditional form and in isolation, would provide an inadequate basis for deep understanding of complex interactions and systems. Such transformative research must hinge on the following intellectual pillars: 21st century statistics, information and decision sciences, and human and institutional behavior. These pillars form the basis for graduate education and research.

The new Entity should support several academic programs that are seen to be crucial for promoting its vision.

PhD In Complex Systems

The committees have concluded that even the most relevant existing disciplinary programs (ORC, EECS), in isolation, are not sufficient to train the types of students that can tackle the interdisciplinary and challenging issues posed by complex societal and technical systems. A new PhD in complex systems should complement these programs and focus on producing new types of global leaders in education and research. The following points highlight some of the differentiating features between the envisioned PhD program and existing programs:

- Anchored in mathematical, behavioral, and empirical sciences with emphasis on data-driven analysis and modeling.
- Engages quantitative social science and field-based research, with a broad focus that encompasses engineering constraints, connections and approaches.
- Relies on engineering domain expertise, as provided by various engineering departments and research centers.
- Typical research will be driven by the challenges of systems-level issues, which arise in various engineering and societal domains (e.g., systemic risk, system architecture, policy).
- The program will attract students with a problem focus but also be open to students that are more interested in particular methodologies.

We expect PhD students from this Entity to be attractive for positions in academia (many engineering departments, business schools, and possibly to departments in social sciences), industry and corporations, and several types of government agencies.

PhD in Statistics

An independent PhD in Statistics is vital for launching the statistics effort at MIT. The details of this degree will follow the general structure of the PhD in complex systems (in terms of requirements and qualifications). The core Statistics curriculum should include Probability Theory, Modern Statistics Theory, and Data Analysis. Because of the fragmentation of Statistics at MIT, the statistics committee feels strongly that this PhD should be delayed until a senior statistician is hired to lead the effort. Committee members repeatedly emphasized that, from the perspective of an applicant to the program, the PhD in Statistics should be completely decoupled from any existing degree at MIT, including the new PhD in complex systems. However, the academic program committee feels that the degrees should share a subset of similar courses in the three pillars of the entity. There is confidence that a satisfactory solution can be found that gives both PhD programs, then one in complex systems and the one in statistics, their unique identity while taking advantage of potential organizational and intellectual synergies in the execution of those programs.

Masters in Statistics

A non-thesis SM degree in Statistics can be very attractive to many MIT students in various departments. This degree is intended to provide the students with in-depth courses in statistics. This comprises courses in modern statistical theory, probability theory, and data analysis. Many of such courses are already taught in various departments at MIT. An alternative to this is a Masters in Analytics that combines both Statistics and Information and Decision Sciences. Once launched, the new Entity will evaluate these two options and consider partnering with other units such as the ORC.

Masters in Technology and Policy

TPP is currently a successful program at MIT with the mission of educating engineers and scientists in responsible leadership of technology development by implementing policies for the benefit of humanity. Given the scope of applications considered by the new Entity, TPP is expected to play an important role in the education of students in the Entity. We believe that additional faculty can be recruited to the program if we coordinate this program with the new Center for Policy initiated at Sloan. While TPP already has a strong core with strong connections to Economics, we plan to strengthen the analytical component of the core requirements

Undergraduate Minor in Statistics

Similar to the non-thesis SM, the minor can be obtained by completing a set of undergraduate courses in statistics. Many such courses are already taught at MIT.

The committees discussed the launch time of such programs. These are reflected in the academic programs report and statistics report. It is understood that launching a new PhD program that is nationally and internationally competitive requires time, not to just design the program, but also to guarantee that it attracts the best students in the world. Nevertheless, these academic programs will be a high priority for the new Entity.

3. Organizational Structure

It is recommend that a new Entity be created with an Institute structure broadly resembling that of IMES. This Entity is expected to report to the SoE, but has dotted lines reporting to the other four schools. While this structure allows for many functions of a department (namely, hiring faculty, offering academic programs, and running contracts), it differs in that faculty lines are held in departments or at the school level.[1] . The driving force for the decision stems from the need to keep the new Entity connected with all departments and schools at MIT. This also creates a positive tension in hiring that maintains the high quality faculty that departments have, while simultaneously expanding the departments' strategic initiatives. The negative aspects of this decision are the challenges faced in hiring new faculty through departments, difficulty in maintaining faculty loyalty to the unit, and the added stress that faculty might face when providing teaching and service to two units. The detailed recommendations of the committee focus on alleviating these drawbacks.

The Entity should have a director and three associate directors. A steering Group comprising the director, associate directors, and other faculty members should be formed. The Steering Group will have the responsibility for developing and managing the integrative functions and initiatives that are essential for this entity to thrive. These include:

- Oversight and management of all academic programs associated with the new entity.
- Fostering, developing, and managing major research initiatives that cut across not only the units within the entity but also other units across MIT.
- Coordinating and developing professional and industrial outreach that again cuts across unit boundaries.
- Coordinating all activities on search, hiring and promotion.

Within this Entity, we recommend the creation of a new Center for Statistics. The center, in coordination with the Entity, will focus on launching the statistics effort at MIT. While the center is an integral part of the new Entity, there is a strong desire to have it be independently visible to the outside world to emphasize the new effort in launching statistics at MIT. The director of the center (associate director of the entity) should be a world-recognized expert in statistics, and efforts for identifying such a leader should begin right away.

Faculty in the new Entity will have two possible memberships. Core Members will have broad responsibilities covering research, teaching, service, and maintaining industrial relationships. Affiliate

[1] This was initially the starting condition for the committee. The committee did, however, consider the alternative of holding the lines within the Entity.

Members will have less formal responsibilities in teaching, but will make other important contributions. For existing faculty who are already at MIT, memberships will need to be negotiated with the Entity director and their department head.

The committees also established a membership structure for departments. By becoming a member of the Entity, a department can participate with the Entity in charting a strategic hiring plan for faculty in certain areas. Searches will mostly be conducted with a committee comprising members of the Entity and selected department members. This structure is intended to alleviate the tension in hiring into a department, but also will help in shaping departments strategic plans. Faculty slots will be allocated to the Entity by the Dean(s) and hiring will be done by the Entity and associated departments jointly.

Faculty promotion and tenure will occur in the departments but with direct involvement of the Entity director. The Entity Director (or a designated associate director) will participate in all the pertinent promotion cases in their entirety in Engineering Council, if the Entity has a similar case in that cycle; otherwise, the Director will not participate. For the other schools, the Entity director will be able to attend a school council if invited by a department head and approved by the dean of the school. The Entity director and department heads will jointly perform annual performance reviews.

Finally, having contiguous space for the Entity is an essential requirement for the success of the initiative. Ideally, we would like a home for all core members, including the projected hires. Practically, it is important that we have space for all new faculty, their students, as well as post docs, research scientists, and visitors.

4. Transition Plan

Core ESD and LIDS faculty will be integrated into the Entity. In addition, a number of other faculty from different schools will join as core members. In particular, a center for statistics will be formed as part of this entity, and faculty in statistics will join the center as core members.

ESD Integration

By transitioning to the Entity, ESD will no longer be a division. The faculty will move to departments (this is with the exception of junior faculty and a small number of faculty who desire to remain part of the Entity; a special arrangement will be made). All primary and dual ESD faculty, if they desire, will become core members in the Entity. SSRC will be repurposed to fit the new vision and will continue to be a cost center in the new Entity with an associate director. CTL will remain independent and reports to SoE (with possible involvement of Sloan).

The Academic Programs Committee has made the following recommendations with regard to ESD's graduate programs:

1. The ESD-PhD will transition into the new PhD in Complex Systems. In designing the latter program, many of the successful features of the ESD-PhD will be retained. Existing students will have a choice between the two degrees, that is to complete their PhD under the existing rules of the Engineering Systems program or the rules of the new PhD in Complex Systems.
2. The MIT School of Engineering will create a new office of professional graduate education to house and support the successful existing masters programs including SDM, LGO, SCM and possibly TPP. This recommendation partly stems from two facts: (i) the programmatic content of these programs

goes beyond the intellectual domain of the new Entity, and (ii) in the new Entity, faculty coming from LIDS, or who are focused on statistics, are largely uncommitted to these programs, at least in terms of their teaching efforts. More so, such a structure will increase the footprint of these programs across the SoE. Faculty members in the new Entity will be encouraged to continue to teach and supervise theses in these programs. As a research focused program, TPP could be housed in the new Entity. In this case TPP should reshape its core classes to be better aligned with the new Entity and to take advantage of the broader set of faculty that will be available to teach core TPP classes.

LIDS Integration

LIDS will be integrated into the new Entity as a laboratory and cost center. The faculty in LIDS will become core members of the Entity. LIDS will continue to have a director (associate director of the entity), and will remain in its current space. LIDS does not have its own academic programs.

Other Faculty and Programs

A number of faculty members from various departments have indicated their strong interest in being core members of the new Entity. This will be accomplished by agreement with their department heads and the entity director. Given the broad intellectual interest of the Entity, we expect direct collaborations with other labs, centers, and initiatives at MIT. These include CSAIL, RLE, MITEI, CCE, and the Media Lab. An advisory board will be formed with members from these units.

5. Strategic Hiring Plan

Three schools have committed slots to be hired in this Entity in the next 3-5 years. Here is the breakdown of these commitments:

a. The School of Engineering has committed eleven slots to support strategic hires in this Entity.
b. The Sloan School has committed two slots to support hires in Statistics.
c. The School of Sciences has committed three slots to support hires in statistics.

It is understood that the strategic hiring plan will be refined once the Entity is launched and collaborations with other departments begin. The most critical hire is a senior faculty in Statistics. At the junior level, we will be considering faculty in statistics, connection and systems science, application domains, and system and information architecture.

6. Resources

All members of the committees agree that this is major initiative that requires substantial resources to succeed and become the world's leading unit for the study of Complex Systems and Statistics. Such resources include 1) space, 2) faculty slots, and 3) recurring funds to support visiting faculty and post docs, as well as to provide seed funding for integrative research and course development. The launching of the Entity will require the dedication of at least four senior faculty and a number of research scientists to carry the responsibility of initiating the research, constructing academic programs, leading the faculty search, and building industrial connections. Needless to say the success of this Entity is contingent on the collaboration and partnership of the various departments in the five schools.

Report on Mission and Scope

Committee Co-Chairs

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1.The Opportunity

Technological advancements including smart and embedded sensors, high speed communication,[1] social networking[2], and real-time decision capabilities have resulted in the emergence of large scale, heterogeneous, interconnected systems. Analyzing such complex systems remains a major challenge for researchers and practitioners alike. Their design and control/regulation is even more challenging.

Systems directly impacting our society often involve the interactions of three heterogeneous aspects (see Figure 1) : 1) an engineered or natural physical system, 2) social behavior of people interacting with the system, and 3) institutional behavior of units such as regulators and markets governing the system. Traditionally, such systems (referred to as socio-technical systems) have been analyzed and (when possible) designed with each of these aspects in isolation. This has resulted in suboptimal and fragile interconnections. The above technological advancements, combined with increased computational capabilities and the ability to collect vast amounts of detailed data give us a new opportunity to holistically, systematically, and scientifically address the broad challenges facing these complex systems.

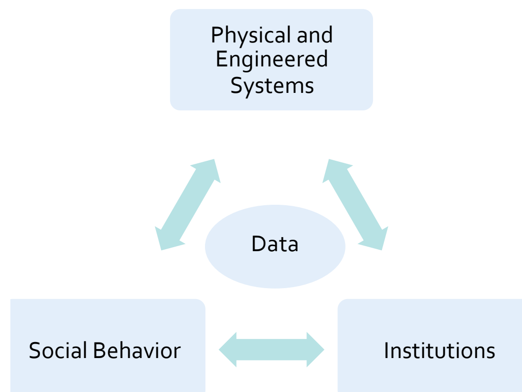

Figure 1

There are many examples of such systems embodying critical societal challenges. Emerging systems including energy, transportation, finance, healthcare, manufacturing, and social networks are particularly interesting. Furthermore, the applications of these systems have direct impacts on people's lives. Some examples include the 2010 flash crash, the 2008 Great Recession, the 2003 New England power outage, and the less-catastrophic-but-more-frequent cascaded delays in air travel due to unexpected weather. This small subset of applications illustrates the need for principled approaches to addressing such complex behaviors (more detailed descriptions are in the Appendix).

We propose the formation of a new Entity at MIT to establish, coordinate, and lead research and educational programs aimed at addressing these complex problems to make a substantial impact on important societal problems.

[1] enabling the transfer of massive data sets in almost real time
[2] enabling fast exchange of people's opinions

1.1 Mission

We propose the formation of a new Entity at MIT to establish, coordinate and lead research and educational programs with the following mission (see Figure 2):

- *Create a research and educational environment that enables analyzing, predicting, designing and controlling complex societal and technical systems.*
- *Create an Institute-wide focal point for advancing MIT's research and educational programs related to 21st century statistics.*

Research in the entity will address overarching challenges including modeling and prediction of system behavior and performance, systems design and architecture, and issues such as social welfare and sustainability, and resilience and systemic risk. Research will connect closely with domain expertise to understand the challenges and opportunities in complex systems of interest. Educational and research methodologies will be anchored in the cross-disciplinary fields of statistics, information and decision sciences, and human and institutional behavior.

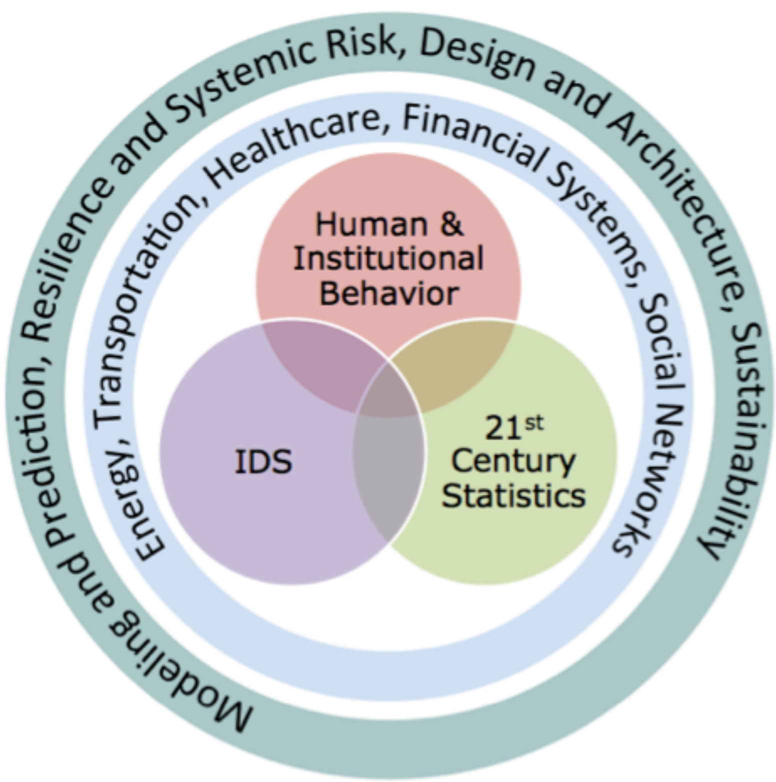

Figure 2: Scope of New Entity

2. Interdisciplinary Education

The proposed Entity embraces the collision and synthesis of ideas and methods from analytical disciplines including statistics, stochastic modeling, information theory and inference, systems and control theory, optimization, economics, human and social behavior, network science. These disciplines are relevant both for understanding complex systems, and for presenting design principles and architectures that allow those systems' quantification and management.

Each one of the above fields, in its traditional form, would provide an inadequate basis for deep understanding of complex tasks and systems. Such transformative research must hinge on the following disciplines, and the interactions amongst them:

2.1 Twenty-First Century Statistics

Statistics is undergoing a revolution enabled by the vast amount of data available from physical, engineered and social systems. This revolution manifests itself in the extremely rapid development of the field at its more traditional core (including probability and statistics) and beyond ((including computational statistics, machine learning and other fundamental algorithmic and computational areas that are critical to complex system analysis"). The landscape for 21st century statistics should address (but not be limited to) the following areas:

High dimensional statistics

This field focuses on studying large data sets from distributions of dimensions higher than the size of the sampled data set. Without additional assumptions such as sparsity or smoothness, the classical methods are ill posed. Work in this area focuses on finding lower dimensional smooth models that can explain the data sets, finding proper model classes that can represent sparsity, and efficient techniques for estimating error bounds.

Machine Learning

Primarily led by computer scientists, machine learning addresses the interface between learning, complexity, and computation. Research in this area spans many theoretical topics as well as practical applications.

Data-Driven Decision Sciences

In situations where physical or mechanistic models are not available, data-driven decisions are the only effective way for understanding decision making. Since making decisions under uncertainty is fundamental to learning, this area provides connection between various fields, including reinforcement learning and adaptive control.

Inference and information theory

This field focuses on areas at the interface of information theory and learning. Since estimation and coding theory have similar roots, the questions of finding compressed models for large data can be viewed and understood from an information theory perspective. This field connects with high dimensional statistics in several ways, including through the study of random matrices.

Uncertainty Quantification

Uncertainty quantification (UQ) involves the quantitative characterization and management of uncertainty in a broad range of applications. It uses computational models, observational data, and theoretical analysis. UQ encompasses many different tasks, including uncertainty propagation, sensitivity analysis, statistical inference and model calibration, decision making under uncertainty, experimental design, and model validation. UQ thus draws upon many foundational ideas and techniques in applied mathematics and statistics (e.g., approximation theory, error estimation, stochastic modeling, and Monte Carlo methods) but focuses these techniques on complex models (for instance, models of physical or socio-technical systems) that are primarily accessible through computational simulation. UQ has become an essential aspect of the development and use of predictive computational simulation tools.

Big Data Applications

This entails deriving hierarchical models from heterogeneous data sets in a given application. Examples of such applications come from energy, health care, and other complex societal problems. Such problems require the understanding of many of the fields described above. Research in this area is critical in both making an impact to the application, as well as providing an evaluation mechanism to the existing techniques.

2.2 Information and Decision Sciences (IDS)

IDS as a discipline builds upon three areas of mathematics: 1) Dynamical Systems, 2) Probability and Stochastic Processes, and 3) Optimization and Game Theory. Such basic areas continue to be vibrant research areas within and outside MIT. Prominent examples of research and education in IDS are described below:

Transmission of Information

Research in information transmission is concerned with fundamental limits of point-to-point and peer-to-peer information transmission in noisy channels. It is centered on information theory which has far reaching implications in problems related to coding, estimation and statistics, and inference.

Control and Decision Theory

The focus of this field is on the modeling, analysis, and feedback controller design for systems described by stochastic linear or nonlinear differential or difference equations, with special emphasis on issues of optimality and robustness (decisions under uncertainty).

Algorithms

Research and education in algorithms address computational aspects of problems in IDS that include complexity and analysis of algorithms in various computational problems including inference, optimization, games, and simulations.

Networks

This is a field in IDS that addresses the impact of network connections on the performance of systems. Networks can be physical, cyber, or social. Networks can interact with other networks of different types resulting in emergent behaviors that are difficult to predict. Most recent attention has focused on large and stochastic networks to understand information flow, bottlenecks, or cascades of reactions.

2.3 Human and Institution Behavior

This field is concerned with nontraditional aspects of modeling human and institutions' behaviors as they relate to particular societal applications. This addresses the behavior of individuals, groups, and Institutions such as markets, regulators, and governments as it impacts the operations and behaviors of systems. Aspects of this field are anchored in the social sciences (e.g., economics, sociology, psychology, political science), management and policy. The collection of large amounts of data on individual and institutional behaviors will enable deriving empirical models that are both consistent with fundamental theories of such behaviors, and actionable from an analysis and design perspective. The Entity will be charged with defining this field in terms of core education and related research.

Rational Decision Theory

This field addresses a framework for human and institutions decision making. Rationality assumes that a decision maker acts to maximize a certain personal reward in the presence of budget constraint. It presents a viable framework for multiple decision makers in the context of game theory. Rational decision theory is typically taught in microeconomics subjects.

Behavioral Decision Theory

This is a field that is tightly related to behavioral economics. It focuses on the study of social, cognitive, psychological, and emotional factors on the decisions of both individuals and institutions. In contrast to *rational behavior* in decision-making, this field addresses *bounds of rationality* acknowledging that decision makers are impacted by the information they have, the time they have to make decisions, and their computational limitations. It naturally interacts with social science studies including cognitive psychology (focusing on mental processes such as attention, memory, perception, and creativity), anthropology, and political science.

Organizational Behavior

This field addresses the study of human behavior in organizational settings, the interface between human behavior and the organization, and the organization itself. Studies in this field range between understanding the individual behavior, group behavior, and institutional behavior. The field also addresses questions of organizational structures to mirror the technical operations of the organization.

Public Policy

This field addresses creation of a public policy with respect to a public issue that is consistent with the law and institutional customs and their potential evolution. The policy-making system is a dynamic, complex, and interactive system and requires continuous evaluation and verification. It can end up with several policy responses (regulation, subsidies) on both national and international levels. Public Policy also deals with the interpretation and construction of information obtained from natural and engineered systems in order to justify or promote particular actions. Such constructions have, in the past, impacted major decisions on societal systems including environmental and health issues.

2.4 Domain Knowledge

Finally, we assert that **'Domain knowledge'** forms the final component of the interdisciplinary educational model. A deep understanding of a specific complex societal and technical system serves to motivate domain-specific challenges and opportunities, as well as to help contextualize education in the methodologies described above. Indeed, history is full of examples showing that research focused on particular applications often leads to fundamental theoretical breakthroughs (e.g., queuing theory, search theory, feedback control theory, and many more).

3. Overarching Challenges

It is important to stress that, while the application domains are quite broad, the educational and research visions of the new Entity are intentionally anchored in the space of mathematical, behavioral, and empirical science. A key aspect of these anchoring disciplines is the reliance on data to create actionable models to support analysis, design and control. The Entity's objective is to make a substantial impact on complex societal problems that could benefit from this viewpoint. **As such, the Entity will focus on the creation of a foundational science to address overarching challenges pertaining to complex societal problems, and will simultaneously engage in several applications to understand the domain-specific challenges and to enable the development of new methodologies**. Below, we discuss four overarching challenges that cut across the intellectual pillars of the new Entity. Other challenges may emerge in the future.

3.1 Modeling and Prediction

While mechanistic models may exist for some physical systems, social behavior is typically learned from data. The challenge is to generate reliable and actionable models from such heterogeneous data sets with only partial information about the underlying processes. New and powerful techniques in modern statistics are needed to support such applications. A powerful utility of such models is prediction. Given the complexity of the underlying applications, prediction methods will be limited by the 'curse of dimensionality' and will demand new innovations in terms of computation and model reduction.

Engineers have succeeded in developing impressive designs because of the power of abstractions. As we confront a new era of data-rich socio-technical systems, the ability to derive abstracted models addressing the interconnections between technical, social, and institutional systems will facilitate substantially impactful research in such systems. Such abstractions can provide quantitative and qualitative understanding that can suggest design architectures and parameterizations of decisions appropriate for the system.

3.2 Resilience and Systemic Risk

The complex interaction between physical systems, cyber layers, and humans has created new challenges in achieving efficiency and optimality while maintaining reliability in contemporary complex man-made systems. *Systemic Risk* is a term used to describe fragility in systems that can result in a cascade of failures in interconnected systems due to small disturbances or large disruptions. One challenge for the Entity is to create a foundational science that allows for measuring, predicting, and containing systemic risk.[3] This theoretical development will emerge from an in-depth understanding of systemic risk in the application of several critical complex systems including the future power grid, the transportation system, supply chain systems, and the financial market. These applications span a wide-range of diversity in terms of interconnections, degree of automation and decentralization, time scales of both evolution and decisions, and finally in term of the role of humans in their operations.
Such transformative research will hinge on the following thrusts: a) Understanding propagation mechanisms of failure in large scale interconnected systems, b) development of a theoretical foundation for inference and early detection of such mechanism and c) development of a methodology for reconfigurable decision systems. The ability to adapt and reconfigure is the main attribute of a 'resilient' system.

3.3 Design and Architecture

Good architecture has been easy to recognize in retrospect but elusive to predict or design. As we transform the nation's power grid, move towards a smart transportation system, or enable global real-time data exchange in financial markets, we must create the mathematical underpinning of network architecture and systematic methods to develop and evaluate design choices and algorithms.

We are aiming to use foundational theory, practical algorithms, and concrete applications to guide us to a framework for secure and efficient architectures. Such a foundational theory of architecture needs to address three challenges: 1) providing an *architecture formalism* that unifies sets of features that persist across different networks and time, that can enable their performance and functionalities, and that can

[3] This should be done while recognizing that such risk constitutes a low probability event in a very high dimensional system.

determine their robustness and fragility, 2) providing metrics and verification tools for evaluation, 3) providing design tools for building a level of reconfigurability to enable modifying existing architectures to meet new sets of specifications.

3.4 Social Welfare and Sustainability

Achieving social well-being, resilience, and adaptation across the domains of ecology, economics, politics and culture requires systematic evaluations of public and scientific innovations. The key to addressing some of these challenges is to enable both quantitative analysis and design of policy. Given the complexity of societal applications as well as the long time frame for resilience, deriving appropriate models it is critically necessary for well-informed public policy.

4. Value Proposition

MIT has demonstrated an aptitude for creating new laboratories and centers to address critical national challenges (e.g., Lincoln Laboratory and the Koch Center). As MIT continues to position itself as the hub for innovations that impact societies at large, it is becoming evident that the formation of this new Entity is critical to maintaining MIT's competitive edge in the broad field of mathematical, behavioral and empirical sciences and its impact on complex societal problems. The new Entity will have an impact on research and education in the following way.

a) Launch a new effort in 21st century statistics and data science as well as consolidate this new effort with existing expertise in information and decision sciences.
b) Create a unique research environment at MIT that bridges domain knowledge with advanced analytical expertise to understand the challenges and exploit the opportunities of complex systems (including socio-technical systems).
c) Create unique and attractive educational programs to provide preparation for research in this field. The outcome of such programs is a new generation of students with expertise across disciplinary domains in the broad field of mathematical behavioral, and empirical sciences. This expertise will position them to be leaders in industrial, academic, and governmental institutions.
d) Provide a hub for expertise in the cross-disciplinary fields of statistics, information and decision sciences, and human and institution behaviors. This hub will lay the foundation for attracting the best faculty complement to support this effort.[4]

[4] This is the basis for a strategic hiring plan, which is discussed in another section.

5. Strategic Hiring Plan

5.1 MIT Faculty

The cores of the ESD and LIDS faculty have agreed to be the initial participants of this vision. Several other faculty members have indicated their interest in playing a substantial role in this new Entity. They come from different schools and cover various application domains and core disciplines that are consistent with the vision of the new Entity. A number of these people are particularly interested in launching the statistics effort. However, we must hire in certain strategic areas to guarantee the success of this initiative.

5.2 Hiring Resources

Three schools have committed slots to be hired in this Entity in the next 3-5 years. Here is the breakdown of these commitments:

a) Eleven slots from the school of engineering to support strategic hires in this Entity.
b) Two slots from Sloan school to support hires in Statistics.
c) Three slots from the school of science to support hires in Statistics.

5.3 Strategic Hiring Areas

It is understood that the strategic hiring plan will be sharpened once the Entity is launched and collaborations with other departments begin. Below, we suggest some preliminary areas of interest with the understanding that hires will happen broadly to support this initiative.

1. Twenty-First Century Statistics

This area is quite broad and covers both methodology and applied work. Hiring from this area overlaps broadly with all five schools at MIT. Priority in hiring will focus on hiring a leading statistician who can provide leadership in establishing a world-class program in 21st century statistics at MIT. Additional junior hires in core statistics will also be necessary. Subareas of interests may include:

a) High dimensional statistics
b) Data-driven decision sciences
c) Machine Learning
d) Inference/Information theory
e) Uncertainty quantification
f) Big data applications

2. Connection Science

This is a broad area describing the foundational theory of networked systems. Such systems can be pure technical, engineered, social, and socio-technical. Within this category, we identify specific areas of interest.

a) Dynamics over networks, including learning, inference, and distributed decisions. The interest ranges from fundamental limits of behavior imposed by the network structure to algorithms for optimization and decision-making.
b) Network dynamics with applications to social networks. Specific interests include prediction, learning, and opinion dynamics.
c) Theory of cascades (failures, adoptions).
d) Learning networks from data. Of particular interest is the inference of causal structures (directed graphs) from time series.

3. Application Domains

We will consider candidates working in applied fields whose methods and expertise are anchored in the main three disciplines. Areas of interest can be quite broad, however, we will give special attention to candidates interested in the main challenges (e.g., sustainability, public policy, systemic risk, safety). We will also emphasize domain expertise where MIT has strategic interest. These include (but not limited to): a) Energy systems, b) Manufacturing, c) Transportation, d) Finance, and e) Social networks.

4. Architecture

We will consider candidates who have made contributions in design architectures. As described earlier in the challenges, architecture refers to questions of layering and information and decision flows. Related questions involve addressing the convergence of sensing, communication, and computing for a given application.

6. Naming the Entity

There are many factors affecting the naming of this new Entity. Simplicity is a key requirement. Several names have been proposed with various permutations: Institute for Systems Science and Engineering (ISSE), Institute for Statistics and Information Systems (ISIS). Another model is to name the Entity after a major donor, or name it after a key figure that allows for fund raising (Vest was proposed by several people). There was a strong feeling that the name needs to include a reference to statistics. Also, there was a unanimous support for this Entity to be an Institute given its ambitious goals, reporting structure to all five schools, and its support for both education and research. Finally a proposal was made to run an Institute-wide contest for naming the Entity and give a big prize for the winner.

7. Appendix

7.1 Appendix A – Applications

Power Grid

The electricity network has been named the greatest engineering achievement of the last century. In the US, it consists of more than $1 trillion in asset value, more than 3,000 generators with about 1 TW of installed capacity, more than 300,000 miles of transmission and distribution lines, and more than 3,000 utility companies serving 130 million customers. The actors in this system consist of generators, transmission and distribution grid operators, market operators, and load serving entities (utilities) that service the end users. Further, the North American infrastructure is divided into three major grids: the Eastern Interconnection, the Western Interconnection, and the ERCOT Interconnection. They are subdivided into approximately 140 geographic areas, each operated by an ISO/RTO that is responsible for balancing the supply and demand in its control area.

To ensure reliable operation, the operators comply with the reliability standards and processes set by the North American Electric Reliability Council and managed by its 10 Regional Reliability Councils. This structure has historically been successful and the grid is 99.97% reliable. However, even with this level of reliability, outages still cost our economy $80B -150B annually. Worse yet, the frequency of large outages has been increasing dramatically; e.g., according to the EIA, the number of outages of 100 MW or larger has increased from 147 during 2000 -2004 to 230 during 2005 -2009.

The grid is in the midst of several significant structural changes, which will likely accelerate the rising trend of large outages. Specifically, there are four key structural changes happening right now that lead to increasing systemic risk: 1) increasing utilization which is inevitably accompanied by a shrinking reliability margin, 2) increasing intermittency and uncertainty as renewable penetration increases, affecting voltage and frequency stability and straining the electricity market, 3) increasingly distributed generation rendering the traditional, centralized, open-loop, preventive N-1 contingency planning approach unscalable, and 4) architectural flux due to the integration of renewable resources and the increased automation of the grid.

The power grid embodies the overarching challenges at the core of the Entity's vision: a need for new predictive models informed by data and addressing the interconnections between the technical, social, and institutional components of the power grid; a need for a principled understanding of systemic risk and its implications for creating a resilient power grid system; discovery and evaluation of new design and architecture choices informed by analysis of information and decision flows together with their interactions with social and institutional behavior; and new perspectives on policy and regulation, again informed by analysis of the interactions among physical, social and institutional behaviors. Addressing these challenges clearly requires interdisciplinary research spanning the areas of statistics, information and decision sciences, and human and institution behavior, making the power grid a prime target application for the new Entity

Transportation

The transportation system spans modes of transportation on the ground, sea, and in the air, and includes the connections allowing transfer of people and freight between modes. Comprising the transportation system are several components, including the physical infrastructure network (including roadways, railways, ports, airports); the vehicles and their drivers (including automobiles, trucks, airplanes, trains, buses, ships); the transportation service networks (including bus, train and flight schedules); the information network providing information about the system status (such as travel times, roadway and airport conditions and delays, etc.); the transportation providers (including airlines, transit companies, railroads); the system controllers (such as the Federal Aviation Administration, the roadway authorities, the transit authorities, etc.); and finally, the users of the transportation system (that is, travelers and goods). The transportation system thus consists of multiple mode-specific networks, all linked together by flows of people and goods across these networks. The level of information and communication provided to the various operators and controllers of these networks varies widely by mode, and is often not shared across modes.

The Wall Street Journal recently reported that Americans spend an average of one week per year stuck in traffic, and daily commutes in Beijing can last five hours, or worse, as was the case last summer when multi-day traffic jams occurred. Congestion also plagues the aviation system. In the recently concluded Total Delay Impact Study commissioned by the Federal Aviation Administration, researchers estimated the total cost of domestic air traffic delays to be around $31.2 billion for calendar year 2007, including $8.3 billion in additional aircraft operating costs, $16.7 billion in passenger delay costs, and an estimated $6.2 billion in other indirect costs of delays. Although many of these delays disruptive and not catastrophic, they can cause severe breakdowns in the aviation system. In December 2010, about 3.5 inches of snow in and around London's Heathrow airport caused 4000 flights to be canceled, forcing some 9500 passengers to spend the night at the airport.

With significant growth projected in the number of cars and the demand for air travel worldwide, a future transportation system that maintains the status quo will not function even at today's current, often inadequate, levels. And, because the current transportation system cannot be scaled up to satisfy these future demands, our future mobility will be limited, global economic growth will be slowed, and reduced access to food, medicine, products and services will degrade our quality of life.

Financial Networks

Modern financial systems exhibit a high degree of interdependence, with connections between financial institutions stemming from both the asset and the liability sides of their balance sheets. While the emergence of financial instruments in the form of credit default swaps and other credit derivative products, loan sales and collateralized loan obligations has improved the possibility for financial institutions to diversify risk, it has also led to more overlap and more similarities among their portfolios. This has increased the probability that the failure of one institution is likely to coincide with the failure of other similar institutions. Combining this with a greater reliance on wholesale short-term finance has increased rollover risk for financial institutions. The turmoil in financial markets in 2007, and the following months has revealed, once again, the intertwined nature of financial systems. While the events unfolded, it became clear that the consequences of such an interconnected system are hard to predict. What initially was seen as difficulties in the U.S. subprime mortgage market rapidly escalated and spilled over to debt markets all over the world. As markets plunged, interbank lending rates started to rise, and soon the market for short-term lending dried up. As an example, the credit crunch ultimately triggered a bank run at the British mortgage lender Northern Rock – something not seen in the UK for over 140 years and in Western Europe for the past 15 years.

The events of the past few years highlight the tremendous negative impact of systemic failure in financial networks on, not only the financial system, but the economy as a whole. Therefore, developing and practicing financial regulations and economic policies that minimize the exposure of the financial network to such systemic risks are of utmost importance to the health of the economy

Engineering Effective Response to Outbreaks of Influenza

Seasonal outbreaks of influenza are costly in human and economic terms. In the U.S. tens of thousands die each year, and orders of magnitude more worldwide. Annual economic losses have been estimated to be tens of billions of dollars, accounting for costs of medical care and loss of life.[5] Pandemics, occurring much less frequently, have the potential to be more disastrous than an exchange between warring nations. According to historical accounts, the 1918-19 Spanish Flu pandemic killed more than 40 million people; more than died during the First World War.[6]

Vaccines traditionally have been considered to be the most effective societal interventions to mitigate the impact of influenza outbreaks. Periods as long as six months may elapse while the vaccine is configured, tested, manufactured and distributed. Changes in human behavior with respect to hygiene and social distancing also constitute first-order control of the spread of infections and have been termed, "Non-Pharmaceutical Interventions" (NPI's). Considered by many to serve as "placeholders" until vaccine becomes available, it is now clear that continual use of diligent behaviors confers great benefits before, during and after outbreaks of contagious illness. Vaccines and NPIs have been incorporated into mitigation policies advocated by public health officials and are widely publicized.

Engineering effective response to outbreaks of influenza aims to derive the greatest value from vaccines, from NPIs and the interaction between these two types of interventions. Current practices for allocating and distributing vaccine are fundamentally flawed, sometimes resulting in its arrival to regions where the illness outbreak has peaked, and where individuals have little interest in becoming

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[5] McKibbin, W. Global macroeconomic consequences of pandemic influenza. Lowy Institute for International Policy, Sydney. http://www.lowyinstitute.org/Publication.asp?pid=345. Published February 2006. Accessed March 4, 2010.

[6] Pandemic flu history. Flu.gov website. http://www.flu.gov/pandemic/history/index.html. Accessed March 4, 2010.

immunized. And NPI's could have even greater impact when targeted at population groups most at risk to transmit or contract illness.

We need to develop new models of transmission of influenza that examine alternative policies for the prevention and control on influenza. New approaches to the distribution of vaccine, coupled with suitably targeted and appropriately timed advocacy of NPIs can saves lives, reduce cases and costs, in the event of a seasonal outbreak or pandemic.

7.2 Appendix B – Other Programs in this Space

Institute for Advanced Studies, Italy

In Italy, *IMT Institute for Advanced Studies* was founded in 2005 (www.imtlucca.it) as one of the four Italian Elite Academic Institutions, based on the model of Scuola Normale Superiore, introduced by Napoleon in 1801. IMT aims at integrating research and graduate education and it has been conceived as an interdisciplinary entity, with a focus on the analysis of different socio economic, cyber physics and technological systems.

The founding Director of the Institute, Fabio Pammolli, currently visiting LIDS, referred to the notion of "The Sciences of the Artificial" and "The Sciences of Design", originally introduced by Herbert A. Simon, to implement an organizational model that aims at reaching critical mass from complementarity and interaction among leading scientists in their respective fields, working on 'mission oriented' problems selected not only for their scientific relevance, abut also for their relevance for society.

The first cohort of permanent faculty members composes a team of 10 between associate and full professors, with backgrounds in economics, statistical physics, optimal control, networks, computer science, statistics, and the humanities. Two years ago, the Institute has moved from a collection of Ph.D. programs to two Ph.D. tracks. One of the tracks, in particular, has been denominated "Information and Decision Systems", and it is conceived around a 'backbone' of fundamental quantitative courses shared by students in different areas. Then, starting from the second year, students choose the problems they work on, consequently deciding the specific field of their specialization.

Center for the Study of Complex Systems: University of Michigan

This Center studies systems like economies, the brain, ecosystems, political systems, social networks, and the Internet that consist of many interacting individuals, nodes, or parts and that produce collective behaviors that exceed and even transcend the capabilities of the constituent parts. The behaviors of interest include:

- **Self-Organization** into patterns, as occurs with flocks of birds, periodicity in disease outbreaks, or residential segregation.
- **Emergency** of functionalities, such as cognition in the brain or the robustness of networks.
- **Chaos**, where small changes in initial conditions ("the flapping of a butterfly's wings in Argentina") produce large later changes ("a hurricane in the Caribbean").
- **"Fat-Tail" Behavior**, where rare events (e.g. mass extinctions, market crashes, and epidemics) occur much more often than would be predicted by a normal (bell-curve) distribution.
- **Adaptive Interaction**, where interacting agents (as in markets or the Prisoner's Dilemma) modify their strategies in diverse ways as experience accumulates to produce cooperative behavior.

Note that these emergent behaviors need not align with the goals of the individual parts. This complex of unintuitive relationships between the micro and the macro makes these systems difficult to analyze, explain, and predict.

Scientific progress in complex systems often requires cross-disciplinary techniques that combine mathematics with computational models and simulations. Scholars in our Center use a variety of quantitative tools including differential equations, statistical mechanics, information theory, graph and network theory, agent based models, cellular automata, Markov processes, matrix algebra, generated systems (e.g., logics and generated groups), and game theory. We often incorporate models, measures, and insights from traditional disciplines -- physics, biology, computer science, economics, and mathematics -- but we do so in novel ways with the hope of identifying properties that hold across a wide range of complex systems.

Mark Newman, a member of this center indicated that the core faculty at the center are members of other departments. The center was initially resourced with 10 slots. The absence of a physical space was cited as a major handicap for collaborations. The center offers an undergraduate minor and a PhD in complex systems.

NETS Program at Penn Engineering (nets.upenn.edu)

The Networked and Social Systems (NETS) Program at Penn Engineering is a new interdisciplinary undergraduate degree program that is jointly administered by the departments of Electrical & Systems Engineering and Computer & Information Sciences at Penn Engineering. The prevalence of networked systems, from technological (Internet, power grid, transportation, telecommunications) to social (Facebook, Twitter, LinkedIn, etc) and financial (e.g inter-bank lending) networks in our everyday lives have made Network Science and Engineering a vibrant research enterprise. However, our mostly stove piped current undergraduate degree programs do not fully prepare the students for research, engineering and entrepreneurship in this domain. The NETS program intends to fill this void, by synthesizing a curriculum that combines Computer Science with Systems Engineering and Operations Research, as well as the Information and Decision Systems side of Electrical Engineering with Economics and social sciences. The generous endowment of Raj and Neera Singh have enabled the recruitment of 4 faculty personnel for this program: 2 in the ESE department and 2 in CIS. In addition the program's core faculty members involves the two cofounders plus an undergraduate curriculum chair.

The curriculum of NETS contains 5 new flagship courses as follows:

- NETS 112: Networked Life (a freshman seminar on network science and systems)
- NETS 150: Market and Social_ Systems on the Internet (a second semester freshman course on networks and algorithms, with web search as an example)
- NETS 212: Scalable and Cloud Computing (a sophomore level course on distributed and cloud computing)
- NETS 312: Theory of Networks (a junior/senior level course on network theory including spectral graph theory and random graph theory)
- NETS 412: Algorithmic Game Theory. (a course on algorithmic game theory, mechanism design)

These courses are combined with the fundamentals of Engineering, Mathematics & Natural Sciences, Social Sciences & Humanities. Students will choose one of the following four major areas of exploration in which they take 6 courses to complete a NETS degree:

1. Networked and Cloud Services

The Networked and Cloud Services track focuses on tools for building services to rival Facebook or Google, with an emphasis on algorithms, data management, artificial intelligence, software engineering, user interfaces, data visualization and more.

2. Theory of Networks and Dynamics

The Theory of Networks and Dynamics track focuses on analysis and design that considers network structure, with an emphasis on optimization, networks, dynamic systems, stochastic processes, decision theory, and more.

3. Economic and Networked Markets

The Economics and Networked Markets track focuses on how institutions and new digital markets are affected by instant digital communication, with an emphasis on network economics, microeconomic theory, algorithmic game theory, sponsored search auctions and more.

4. Technology and Society

The Technology and Society track focuses on cutting-edge social-impact questions with an emphasis on technology and policy.

All four tracks share a common core that includes the most rigorous quantitative courses in CS, Information and Decision Systems, and Systems Engineering curriculum as well as mathematics. These include courses such as linear algebra, probability, statistics, programing, data structures, algorithms, dynamic systems, optimization, stochastic systems analysis, game theory and microeconomics.

The Program is highly selective: students either directly apply to NETS when they apply to Penn Engineering, or transfer into the NETS major in their sophomore year. The yield of the program is higher than the yield for Penn Engineering.

The first class will graduate in 2014. Students have been getting internship opportunities from their freshman year and Tech employers such as Google, Facebook, and Microsoft find them to be better prepared than typical EE or CS graduates.

Appendix C – Charge to the Mission and Scope Committee

The Scope Committee will define the mission, educational and research programs, and strategy for a new entity comprising the domains of information and decision systems, theory and application of Statistics, and socio-technical systems. The committee will chart a 3-5 year plan for the creation of a first-rate unit that is anchored in all five schools at MIT, that enables MIT to address complex socio-technical and large-scale societal problems with rigor, and that creates a culture of interactions between disparate domains on both the education and research fronts. The committee will identify the key players of this unit and define mechanisms for collaborations and inclusive interactions. The committee will evaluate the necessary faculty complement to support this mission and will prepare a faculty-hiring plan. The committee will identify necessary resources to guarantee success.

Report on Academic Programs

Committee Co-Chairs

Thomas Magnanti	Institute Professor, ORC
Olivier de Weck	ESD, AA

Committee Members

Saurabh Amin	CEE, LIDS
Munther Dahleh	EECS, LIDS, ESD (ex officio)
Steve Eppinger	Sloan, ESD
Dan Hastings	ESD, AA
Chap Lawson	Political Science
Eytan Modiano	AA, ORC, LIDS
Dava Newman	AA, ESD
Asu Ozdaglar	EECS, LIDS
David Simchi-Levi	ESD, CEE

Committee Staff

Annmarie Foley	ESD

Table of Contents – Academic Programs

1. Executive Summary

The Academic Programs Committee has evaluated the Engineering Systems Division (ESD) graduate programs and made recommendations for the future of these programs as well as the programs associated with the new Entity focused on analyzing, predicting, designing and controlling the behavior and performance of complex societal and technical systems (natural and engineered systems with special attention to socio-technical systems). In its deliberations the committee had to strike a balance between preserving the best features of the existing programs, while recommending principles and pathways for future doctoral and masters programs that would strengthen MIT's overall position in the area of complex systems research and education.

We recommend that

1. The MIT School of Engineering create a new office of professional graduate education to house and support the successful existing programs SDM, LGO, SCM and possibly TPP. Faculty members in the new Entity would be encouraged to continue to teach and supervise theses in these programs. As a research focused program, TPP could be housed in the new unit. In that case TPP should reshape its core classes to be better aligned with the new unit and to take advantage of the broader set of faculty that could be available to teach core TPP classes.

2. The new Entity creates a new PhD program in complex systems that would be directly aligned with the vision and mission of the new Entity and its three intellectual pillars: Information and Decision Sciences (IDS), Human and Institutional Behavior (HIB) and 21st Century Statistics. This new program would be designed by the constituent faculty of the new Entity after it is launched on July 1, 2014 and will be expected to launch during the 2016/17 academic year. This doctoral program should not compete with, but should complement, existing doctoral programs at MIT such as those of EECS and the ORC.

3. The new statistics PhD program being developed by another committee is built on a common platform of shared courses with the new Entity's PhD program (and perhaps the PhD program at the Operations Research Center).

This report is divided into several sections:

1. Committee Operations
2. Mission of the New Entity
3. Assessment of Current ESD Programs
4. Principles for Future Academic Programs
5. Summary of Recommendations
6. Appendix A – Committee Membership and Charge
7. Appendix B – Schedule of Meetings
8. Appendix C – Narrative about the New PhD
9. Appendix D - School of Engineering Office of Professional Programs (OPP) Recommended Attributes

2. Committee Operations

The membership and charge to the committee are shown in Appendix A. The committee met weekly between January 1, 2014 and March 31, 2014 and minutes from each meeting, as well as associated data were recorded and made available to the committee members on an internal wiki. January was dedicated to initial organizational meetings, data analysis and learning about the ESD PhD program. February was dedicated to the four masters programs, while March focused on coordinating with faculty and synthesizing our findings and recommendations. The detailed schedule can be found in Appendix B.

In the course of its deliberations the committee met with faculty members from ESD, EECS/LIDS as well as the ORC and presented its preliminary findings to the ESD faculty for feedback. We also met with the ESD doctoral students as represented by the Engineering Systems Student Society (ESS) as well as the program directors from all masters programs mentioned in this report.

After the committee began its work it was suggested that the committee should also consider the future inclusion of the Masters in Transportation (MST) program and the doctoral program in transportation in the new Entity[1], however we decided that this exceeded our original charge and that there was not enough time to do justice to this additional request. Nevertheless, Prof. Magnanti and Prof. Dahleh met with Prof. Buehler, the department head in CEE to discuss the transportation program. This discussion confirmed that inclusion of the transportation program was beyond the current mandate of the committee. In the principles discussed below we do lay out some general recommendations that should help to facilitate the decision as to whether or not to include new programs in the Entity, even if these are not specific to the transportation program.

[1] The transportation program (both masters and doctoral level) are currently managed by the MIT Department of Civil and Environmental Engineering (CEE).

3. Entity's Mission

The assessment and design of the education and research of any academic unit cannot be made in a vacuum, but should be aligned with the unit's overarching intellectual, organizational, and programmatic footprint. In parallel with this Committee's deliberations, three other committees were examining the mission and organizational structure of the new Entity as well as the development of graduate programs in the area of statistics. Although much the Committee's activities could have been undertaken independently (especially the assessment of the current ESD graduate programs), the Committee felt it important to align our recommendations with those of the other committees, especially with the emerging mission of the new Entity. As such, our deliberations were informed by and aligned with those of the Mission Committee, which has recommended the following mission statement and an overall structure of the new organization as indicated in Figure 1.

4. Mission Statement

The mission of the new Entity is described as follows:

- *Create a research and educational environment that enables analyzing, predicting, designing and controlling complex societal and technical systems.*
- *Create an Institute-wide focal point for advancing MIT's research and educational programs related to 21st century statistics.*

Research in the Entity will address overarching challenges including modeling and prediction of system behavior and performance, systems design and architecture, and issues including social welfare and sustainability, and resilience and systemic risk.

Research will connect closely with domain expertise to understand the challenges and opportunities in complex systems of interest.

Educational and research methodologies will be anchored in the cross-disciplinary fields of statistics, information and decision sciences, and human and institutional behavior.

There are several implications in the articulation shown in Figure 1.

The intellectual core of the Entity will be mathematical, behavioral and empirical sciences, built upon three core foundations: 21st Century Statistics, Information and Decision Sciences, and Human and Institutional Behavior. Further information on these foundations can be found in the Mission Committee Report. Research in the Entity would include theory, modeling and applications, but the Entity itself would not be limited or focused on any particular application or domain. Although some faculty will be domain experts, domain knowledge would typically reside in departments and research centers outside the Entity. Much of the domain specific, application research would expect to examine (but not exclusively) issues such as systems performance, robustness and resilience, flexibility, systemic risk, decisions and policy, and architecture.

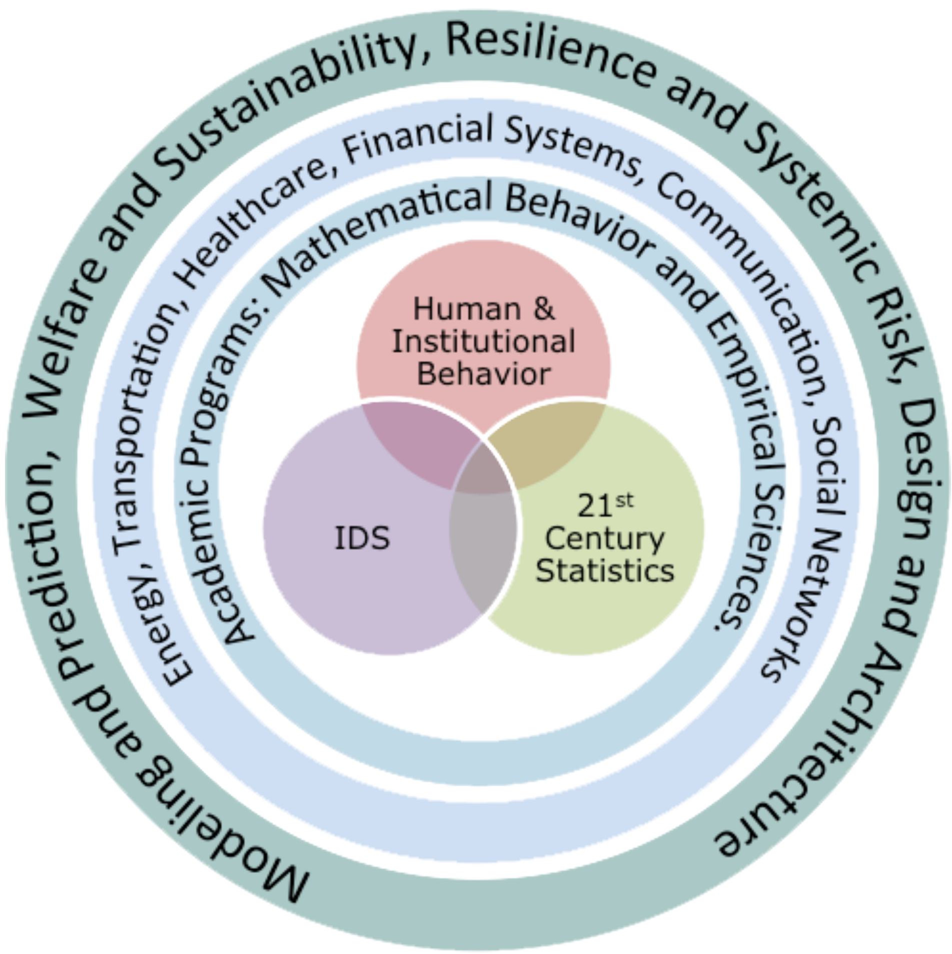

Figure 1: Representation and scope of New Entity

5. Assessment of Current ESD Programs

The committee spent about two-thirds of its time reviewing data and interviewing stakeholders associated with ESD's current academic programs and about one third of its time recommending principles and structures for the academic programs of the new Entity. In this work the committee relied on past Visiting Committee reports, the report by the Rivest Committee as well as data provided by the Provost's Office as well as by the programs themselves. The focus of these efforts was not to provide a comprehensive assessment of each program (as a Visiting Committee report might). Rather, we sought to inform ourselves sufficiently about these programs to understand whether they would be improved as a result of incorporation into the new Entity.

First, we reviewed data obtained from the Provost's Office as well as from the Office of the Dean for Graduate Education (ODGE). The data revealed first an important trend regarding master's degree students in the School of Engineering:

- The number of Master's degree students in the MIT School of Engineering has decreased in every department since 2004 (average -20.8%) except for ESD (+37%).
- Masters students at Sloan have increased dramatically (+45%) since 2004. This is driven by the introduction of new Executive MBA and Masters in Finance (MFin) programs.

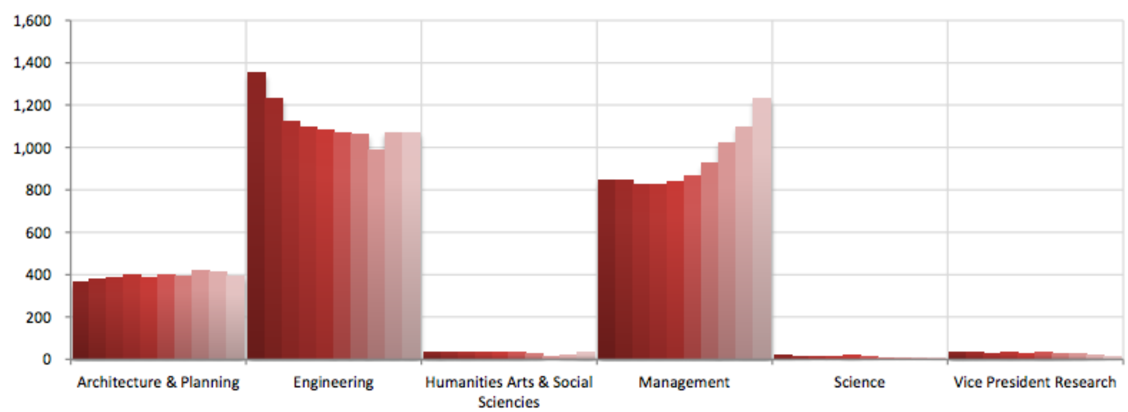

Figure 1: Evolution of Masters Students at MIT between 2004 and 2013

This development raises a series of important questions:

- What is the role of master's degree students in the new Entity and more broadly in the School of Engineering?
- Should there be a distinction between research oriented masters students who intend to obtain a doctorate and professional masters students who will return to industry?
- How should the master's degree programs best be supported and advised?
- Will the new Entity accept students into these programs?

The committee then focused in particular on the ESD Doctoral Program. This program was founded in 2003 and has graduated about a dozen of students per year. It incorporated the earlier interdepartmental Technology, Management and Policy (TMP) program, which had graduated about 4-6 students per year up to that point.

We were impressed by the doctoral students with whom we met and by the caliber and "interestingness" of the work they are doing. ESD doctoral students often have several years of professional experience before beginning the program, and those with whom the committee met were thoughtful and mature. The data we reviewed indicate that ESD students finish as fast or faster than every other doctoral program at MIT and have as low or lower attrition rates.

The data we reviewed and the reports we heard from faculty members also indicate that many ESD students find good placements in academia (including at other programs at MIT) and that ESD clearly competes well with the best systems engineering programs in the world for applicants and placements. About 45% of ESD doctoral students move to academia and many of them secure tenure track positions at respectable tier one universities, or at new universities such as Masdar Institute or SUTD. Approximately 40% assume positions in leading industries. Roughly 15% accept posts in government agencies or with NGOs.

Finally, reports of students and faculty made clear that ESD's "problem-driven" (rather than "method-driven" orientation) and methodological eclecticism (e.g., embrace of field work as well as quantitative analysis) are attractive features of the program. ESD doctoral students and alumni are motivated and driven by a desire to solve societal problems that involve complex socio-technical systems (such as energy, transportation, environment, healthcare and others). The domain knowledge is acquired through a combination of individually selected classes as well as fieldwork. This problem-orientation means that for many ESD doctoral students the question they choose to address drives the choice of methods or algorithms, rather than the method they learn driving the choice of question. About three-quarters of ESD/TMP theses do use quantitative methods such as optimization, statistics and analytics according to an analysis conducted by the Engineering Systems Student Society (ESS), see Figure 3 below, but all students receive some exposure to other methods and many use such methods in their work.

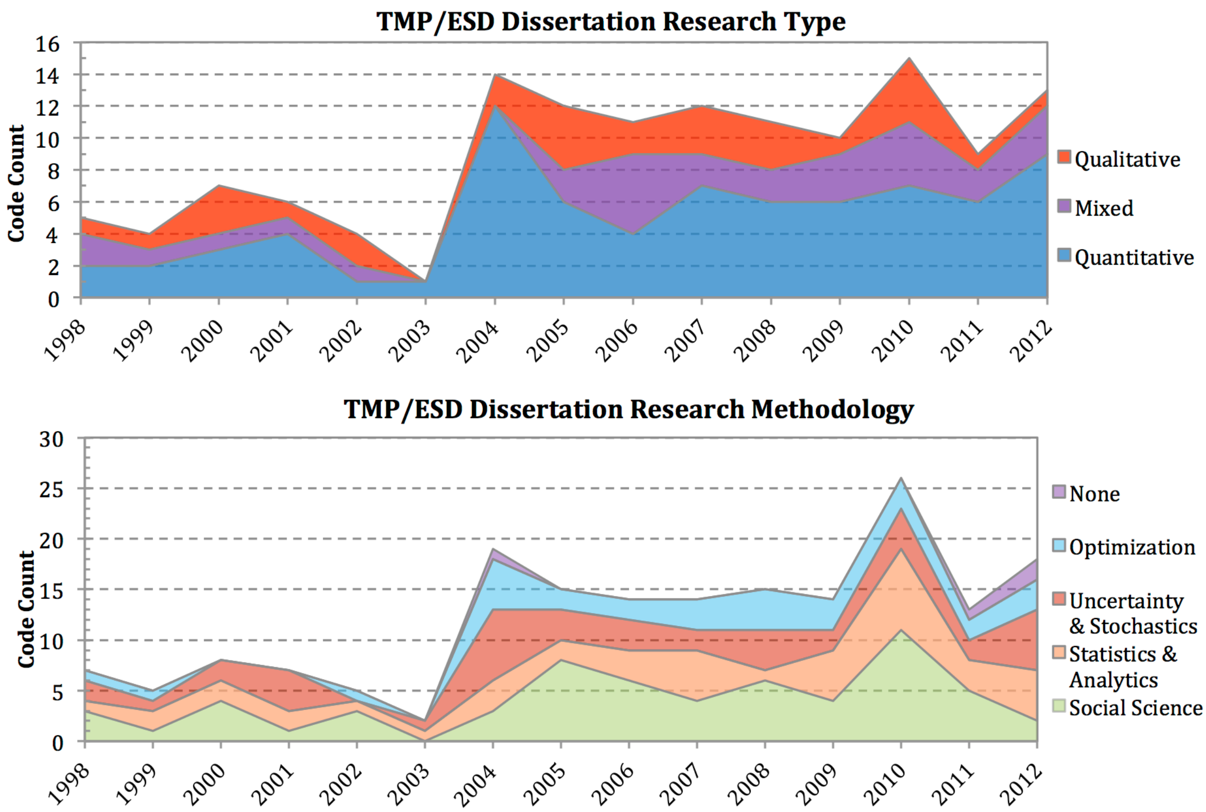

Figure 2: Categorization of TMP/ESD Doctoral Theses by ESS

Several faculty members involved with the program expressed concern that the quality of the ESD doctoral students was uneven and that many ESD students who did go into academia were not placed at peer institutions. We suspect that similar points could be made about many other doctoral programs, but we acknowledge concerns that the left-hand tail of the distribution may be fatter in ESD than in many doctoral programs at the School of Engineering. We also heard scattered reports that ESD students might not always have enough grounding in certain methods to be regarded as world-class by potential competitors on the job market or by faculty in some other programs at MIT, and a majority of ESD doctoral students likewise indicated that they would welcome changes to the program that would bring the program closer to the research performed by LIDS or the ORC. The broad range of backgrounds of the students admitted, the way in which the general exams are administered, the absence of a qualifying exam, and the flexibility in the ESD curriculum collectively make it more difficult to identify and weed out students who do not meet the highest academic standards.

These reports lead us to believe that doctoral training at MIT in systems design and analysis could be strengthened by enhancing the quantitative methodological core of the program (as described by the mission statement) and introducing a qualifying exam similar to that of other doctoral programs in the School of Engineering. We believe that these changes could be accomplished without sacrificing the problem-driven orientation that attracts many top students to ESD. We also believe that ESD's methodological eclecticism could be preserved by exposing students to a variety of research methods in the course of their instruction, by encouraging those students who wish to conduct field work for their dissertations to take additional classes in social science methods outside the Entity that will give them the necessary skills, and by involving faculty from the social sciences or the Sloan School of Management who may be more familiar with such methods in advising such students.

As with ESD's doctoral program, we found much to admire in the four Masters programs we reviewed. Each of these programs operates differently from the others, involves a different set of faculty members, draws a different set of students, and serves a different set of (valuable) external constituencies. Although, with the partial exception of TPP, these programs are not primarily research-oriented, we believe that all contribute crucially to MIT's mission.

One of the reasons for the relatively high admission yields (see Figure 4) is that some of these programs such as SDM and LGO are essentially unique and that many applicants apply nowhere else.

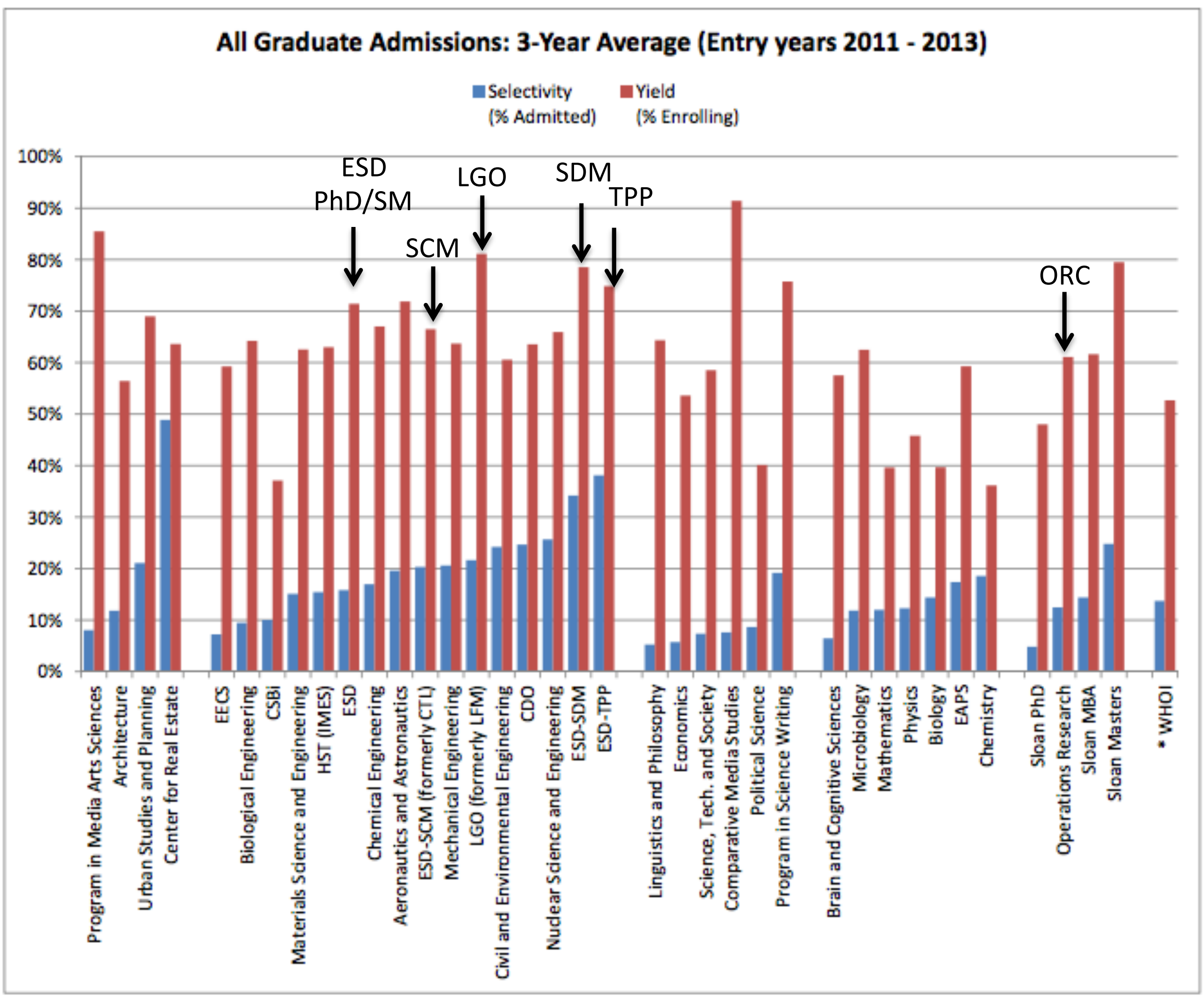

Figure 3: MIT Graduate Admissions Statistics 2011-2013

One theme that emerged with regard to many of the programs we reviewed (including the ESD doctoral program) was the dependence on a small number of faculty to teach some classes crucial to the students' course of study. In some cases, the departure or retirement of a single faculty member would leave a gap in the core curriculum, and in some cases there is no "Plan B" for such an eventuality. In other cases, programs relied or were prepared to rely on non-faculty for a significant portion of instruction and even advising. With respect to the doctoral program, we believe that the number of faculty members attracted to the new Entity will be large enough to address this challenge. In the case of TPP, we believe that additional faculty can be recruited to teach if we coordinate this program with the new Center for Policy initiated at Sloan. The recommendation to create a new Office of Professional Programs (OPP) follows directly from this observation as well as from the fact that the professional orientation of the masters programs is not completely aligned with the research focus of the new Entity or with the professional interests of many of the expected constituent faculty. More so, the committee feels that housing such programs in the SoE OPP will provide better integration of the programs into other engineering departments. Other mechanism within the SoE to effectively administer and ensure the health of these programs may be proposed as an alternative to OPP.

Despite the fact that these programs are strong on their own and are relevant to the new Entity, we feel they would profit from being administrated by a school-level office.

One overarching reason to place the master's degree programs (LGO and SDM) in OPP is that, while the new Entity is relevant to these programs, the Entity's intellectual footprint in the programs is only one of many from Engineering.

In addition, a large fraction of the potential core faculty in the new Entity, particularly those from LIDS, have not participated in these programs, and are not likely to participate in or support these programs in the future.

Also, with the exception of SDM, the core courses for these programs are not taught by core ESD faculty.

The following tables contain our summary of the assessment for each of the programs, including their vision and mission, strengths, weaknesses, concerns, relation to ESD and recommendations for the future.

Table 1: Assessment of Masters Programs

	Vision/Mission	Strengths	Weaknesses	Concerns	Relation to ESD	Recommendations
TPP	• Educate engineers and scientists in responsible leadership of technology development by implementing policies for the benefit of humanity	• Important area • Program longevity and branding • Good multi-disciplinary core (economics, law, modeling, public policy) • Linkages to research • Draws UG students from good schools and feeds to PhD program • Internships—send to Washington, fully funded, and other countries	• Thin faculty bench strength (law, public policy, small core committed faculty) • Lack of institutional commitment by contributing schools and departments	• High acceptance rate from applicant pool (about 30-40%) • Vetting of applicants sent by foreign governments	• Reports to ESD • Faculty involvement in ESD • Leads to PhD	• Keep as a program in the new Entity • Strengthen the analytical part of the program • Limit acceptance rate • Coordinate with new Sloan Center on Policy

Table 2: Assessment of SDM

	Vision/Mission	Strengths	Weaknesses	Concerns	Relevance to ESD	Recommendations (TBD)
SDM	• To educate future technical leaders in architecting, engineering, and designing complex products and systems, preparing them for careers as the technically grounded senior managers of their enterprises • To set the standards for delivering career-compatible professional education using MIT's most advanced information and communication technologies	• Offers a single degree in Engineering and management • Distance option (unique) • Most required classes taught by faculty • Strong industrial support • Students perform very well in classes	• As its own profit center SDM needs to consistently admit over 40 students to avoid a financial loss, which may lead to variability in admitted student quality	• Faculty involvement in the core (small bench strength) • Lack of faculty resources to teach core courses	• Strong involvement in teaching and supervision (both affiliated faculty and teaching staff) • Administratively managed by ESD • Directors report to Sloan and Dean of Engineering and Director of ESD (clarify in future)	• Should have a wider footprint in engineering • More participation from AA, MechE, and EECS • Should be housed in SOE OPP

Table 3: Assessment of LGO

	Vision/Mission	Strengths	Weaknesses	Concerns	Relevance to ESD	Recommendations (TBD)
LGO	• A partnership between MIT and industry that is the premier program for developing leaders of operations-oriented companies who bring both a management perspective and deep technical understanding • To generate cutting edge knowledge at the intersection of engineering and management, and to educate leaders to address the world's most challenging operations problems	• Most required classes taught by faculty • Strong industrial support • Students perform very well in classes • Internship program (6-months) • Core includes probability, statistics, and optimization	• 40% of LGO students select ESD as their engineering department (imbalance) • Concentrated in ESD and MechE	• Potential drift toward a Sloan-only program • Insufficient involvement of Engineering faculty as theses supervisors	• Strong involvement in teaching and supervision (both affiliated faculty and teaching staff) • Administratively managed by ESD • Directors report to Sloan and Dean of Engineering and Director of ESD (clarify in future)	• Should have a wider footprint in Engineering • Strengthen manufacturing emphasis across departments • Should be housed in OPP with connections to Sloan

Table 4: Assessment of SCM/CTL

	Vision/Mission	Strengths	Weaknesses	Concerns	Relevance to ESD	Recommendations
SCM	• Provide a global education in supply chain	• Integrated full program with Industry • Top program in the world • Collaborative effort internationally	• Core taught by Research scientists • Minimal faculty involvement in projects • Projects are too short for a masters	• Why isn't Sloan more involved? • Over reliance on a single faculty leader	• SCM is important • SCM students are admitted under the ESD unit • The program is completely administered by CTL • Unlikely that SCM will become PhD students • Projects are not connected to ESD faculty	• Stay as a bundle and part of CTL • Coordinate admissions with OPP • Increase involvement of Sloan Operations Management (OM) faculty

6. Principles for Future Academic Programs

Before discussing recommendations for future programs, the committee decided to establish some guiding principles for the establishment and operation of both existing and future programs in the new Entity.

- We should aspire that any future academic program be the best program of its kind in the world.
- Any educational program offered should be supported broadly by the constituent faculty.
- The programs should be aligned with the vision and mission of the new Entity.
- The core of the teaching should be in the areas of mathematical, behavioral, and empirical sciences (information and decision sciences, human and institutional behavior, and statistics).
- Domain knowledge in areas such as energy, transportation, health care, manufacturing, critical infrastructures etc.... should be acquired, with guidance from the thesis committee, through taking classes and collaborating with the various existing departments and research centers.
- The programs created should not duplicate or compete with existing programs (e.g., the doctoral program of ORC or in EECS) but complement them. In areas where there is overlap, this overlap should be by design and should be coordinated with the neighboring units.
- New programs might be added over time as long as their inclusion is consistent with the above-stated principles.

Regarding the doctoral program, the committee considered the four high-level alternatives shown in **Table 5** below.

Table 5: Four High-level Alternatives

Program Architecture	Potential Advantage	Potential Disadvantage
No doctoral program		Lack of "research engine" No common focal point for the new Entity faculty
Continue ESD PhD with some improvements	Builds on existing program	Perception of varied quality Potentially too broad
"Virtual" PhD program with dual key admissions in departments (similar to CSE program)	Ties unit strongly to departments	Smaller pool of applicants Danger of fragmentation of the program into sub-cohorts with little synergy
New modular PhD program with common core	Establishment of common core in complex system research Centralized quality control	More work to create Potential competition with the ORC program

7. Summary of Recommendations

1. A new Doctoral Program should be created with focus on complex systems and aligned with the new Entity's vision and mission. This doctoral program should be the first-ranked of its kind and attract the strongest candidates from across the world and be officially launched by September 2016.

2. The doctoral program core courses should focus on mathematical, behavioral, and empirical sciences (information and decision sciences, human and institutional behavior and statistics) and should be coordinated closely with the ORC. The detailed requirements and structure of the program should be designed by the constituent faculty after the new unit is created on July 1, 2014.

3. The School of Engineering should create a new Office of Professional Programs whose mission would be to coordinate with the Sloan School of Management and to actively support and manage the professional masters programs, in particular LGO, SDM and SCM, and possibly TPP. See Appendix D for a recommended list of attributes for this office.
4. Even though the three programs LGO, SDM and SCM would not be housed in the new Entity, individual faculty members would be encouraged to continue to be engaged in these programs.

5. We recommend that the new program in Statistics not be a fully stand-alone program. Rather we envision a platform-based approach where core classes in the new Entity's PhD program, the statistics program and the ORC program would be shared, even if these doctoral programs all maintain a unique identity. (*This is not completely aligned with recommendations from Statistics*).

6. The Technology and Policy Program (TPP) could continue and be housed within the new Entity. The TPP students might choose to later apply to the PhD program and faculty in the new Entity will teach classes for TPP. If the TPP were housed in the new Entity, its director would report to the director of the new Entity (*need to discuss*).

7. The current ESD doctoral students as well as those admitted during the AY14/15 and potentially those admitted during AY 15/16 will be grand-fathered under the existing rules of the ESD PhD Program, but would also have the option to switch to the rules of the new program.

In terms of a schedule going forward we recommend that these changes be made over the next 18 months and be in place by September 1, 2016 at the latest.

8. Appendices

Appendix A – Membership and Charge to the Academic Programs Committee

Committee Chairs

Thomas Magnanti (Institute Professor, ORC) – co-chair
Olivier de Weck (ESD, AA) – co-chair

Committee Members

Dan Hastings (ESD, AA) – Former Dean of Undergraduate Education
Eytan Modiano (AA, ORC, LIDS) - Associate Head of AA
Steve Eppinger (Sloan, ESD) - co-lead of SDM program
Dava Newman (AA, ESD) - director of TPP
Saurabh Amin (CEE, LIDS) - new faculty member in CEE
Asu Ozdaglar (EECS, LIDS) – admissions chair in Area I in EECS
Chap Lawson (Political Science) – representative for the Social Sciences
David Simchi-Levi (ESD, CEE) co-lead of the LGO program

Staff

Annmarie Foley (ESD)

Charge to the Academic Programs Committee

The education committee is charged with defining a framework for the best masters and PhD programs to serve the new organization and MIT.

It will first evaluate the state of the academic programs currently affiliated with ESD and will document their objectives, strengths, and weaknesses, and suggest a course of action for the future.

The future actions could include increasing the support for various programs, suggesting new admission and qualification standards to strengthen the programs, relocating and altering certain programs to be managed by a more appropriate unit. The committee will engage all stakeholders involved with these programs including faculty directors, staff, students, and sponsors. The committee will benchmark these programs against other programs at MIT and outstanding peer programs elsewhere and will summarize the findings and recommendations in a written report. The committee will incorporate the initial recommendations of both the 'scope committee' and the 'statistics committee.'

The specific tasks of the committee are to:

1. Examine the current state of ESD affiliated Programs: ESD PhD, SM, LGO, SDM, TPP and SCM.
2. Benchmark the ESD SM and PhD against EECS, AA, and ORC programs from which LIDS draws its students.
3. Determine the potential relationship of the LIDS faculty to the current ESD Master's degree programs and the most appropriate academic home for these programs.
4. Define the best masters and PhD programs to serve the needs of the new organization and MIT including a range of alternatives with a time horizon of 5 years, while coordinating with the other committees through their co-chairs.
5. Enumerate several pathways and select one of the paths and make specific recommendations on how current programs can be strengthened while moving to the desired future state of educational programs to serve the new organization.

In its work under the first task the committee should answer the following questions about the ESD PhD program in particular:

Admissions

1. Who does the ESD-PhD program serve? (faculty, areas of research…)
2. What unique students' profiles are attracted to this program that are not supported by other PhD programs?
3. How are applicants evaluated? What strengths are being sought in applicants to the program?
4. How strong is the pool of applicants compared to other programs at MIT?
5. How can the program be benchmarked against other similar programs outside MIT?
6. How has the original requirement for a master's degree and the recent introduction of a pre-doctoral track (requiring only a BS degree) affected the program?
7. Which departments or schools are competing for the same students?

Requirements/Qualifications

1. Is the doctoral qualifying process and the general examination tied to building a strong core competency for candidates?
2. The ESD PhD requires a total of 150 units and students can choose from a wide range of courses. Are there paths in this program that can result in weak preparation?
3. The three-legged architecture of the current program is based on a set of three core classes (ESD.83, 86 and 87), an area of depth in methodology and an area of depth in an application domain. Evaluate the implementation of this program and its success in providing uniform training for students. Suggest ways in which this program can be improved.
4. Examine the ways in which the current architecture of the program is a model for future programs.

5. Compare the ESD-PhD architecture against models in different departments that require fewer courses and have a different balance of coursework and research as well as a different balance in depth vs. breadth.
6. What is the research culture of the current program including interactions between students and their advisors, between students and their committees and expectations for novel contributions and publications in peer-reviewed journals? In particular, document the role of research scientist in the advising of PhD thesis and compare to other departments.

Alternate Pathways

1. The new organization might include faculty from ESD, LIDS, and other academic units. Therefore, the constituent faculty could currently be associated with different PhD programs. What are alternate models going forward? A single PhD program or multiple PhD programs within the new unit serving all of its faculty, a decentralized model using departmental PhD programs, a hybrid model, or other alternatives.

2. Should admission to the PhD program be through the new organization, through affiliated departments, or through a two key admission model as in MIT's program in Computational Science and Engineering?

Appendix B – Schedule of Meetings

January 9, 2014 - Initial Organizational Meeting

January 16, 2014 - Data Review Meeting

January 23, 2014 - ESD Student Society Presentation

January 30, 2014 - ESD PhD Program

February 6, 2014 - Technology and Policy Program (TPP)

February 13, 2014 - System Design and Management Program (SDM)

February 20, 2014 - Leaders for Global Operations (LGO)

February 27, 2014 - Supply Chain Management (SCM)

March 4, 2014 - Open Discussion

March 13, 2014 – Meeting with ORC Leadership

March 20, 2014 – Discussion of Committee Recommendations

March 27, 2014 – Review and Approval of Final Report

Appendix C – Narrative about the New PhD

MIT's various departments and schools are consistently ranked among the very best of the nation. Besides their obvious strengths in research, a large factor in this widely shared assessment is the high quality of their educational programs. Innovation in education is one of the cornerstones of the broad societal impact of the proposed Entity.

The various committees have come to the realization that the most relevant disciplinary programs, by themselves, are not sufficient to educate the kind of students that can tackle the interdisciplinary and challenging issues posed by complex societal and technical systems. In the areas relevant to the new Entity, MIT offers several rigorous SM and PhD programs in disciplines such as Electrical Engineering and Computer Science (EECS), Economics, and Management. Additionally, the Operations Research Center (ORC) offers both SM and PhD programs in Operations Research that are complementary to the new PhD program. These traditional programs have been enormously successful in their mission of educating generations of scientific, technical, and societal leaders. Despite their individual success, we envision that a new PhD in complex systems offered by the Entity will produce new national and international leaders in education and research pertaining to complex societal and technological systems.

The following points highlight some differences between the envisioned PhD program and existing programs:

1. Anchored in mathematical, behavioral, and empirical sciences with emphasis on data analysis, modeling and simulation, the educational program will also include human and institutional behavior (bringing elements of economics, cognitive psychology, political science, and management together with technical fields in information and decision sciences, socio-technical systems engineering and statistics).
2. Engages quantitative social science and field-based research with a broad focus encompassing engineering constraints, connections and approaches.
3. Relies on engineering domain expertise as provided by various engineering departments and research centers and initiatives.
4. Typical research is driven by big challenges of systems-level issues arising in various engineering and societal domains (e.g., systemic risk, system architecture, policy).
5. The program would be attractive to students with a problem focus similar to those in the current Engineering Systems doctoral program, but also be open to students that may be more interested by particular methodologies.

We expect PhD students from this Entity to be attractive for positions in academia (many engineering departments, business schools, and possibly to departments in social sciences), corporations, and government agencies.

Appendix D – School of Engineering Office of Professional Programs (OPP) Recommended Attributes

- Focused on professional education programs at MIT not offered directly by the Sloan School of Management
- Coordinates the programs jointly offered with Sloan (e.g. SDM and LGO)
- Sets targets and manages all professional masters programs including SDM and LGO
- Coordinates the SCM program (even if this program continues to be housed in CTL)
- Headed by an Associate Dean of Professional Programs who reports to the Dean of Engineering
- OPP makes sure that all teaching assignments are clearly set in negotiation with the Dean and the department heads
- Develop and exploit the full range of offerings from degree, certificate to summer short programs
- Innovate in pedagogy for professional programs from on-campus, on-site, and remote delivery including MOOCs
- Enhance industry partner relationships and coordinate with the Industrial Liaison Program (ILP) and the individual programs
- OPP has its own budget as well as a small staff attached to the SOE to help coordinate schedules with the registrar, facilitate admissions, career development and joint events across programs

Report on Statistics

Committee Co-Chairs

Emery N. Brown	BCS, IMES
David Gamarnik	Sloan, ORC

Committee Members

Victor Chernozhukov	Econ
Munther Dahleh	EECS, LIDS, ESD (ex officio)
Dan Frey	MechE, ESD
Sham Kakade	MSFT
Tommi Jaakkola	EECS, CSAIL
Devavrat Shah	EECS, LIDS
Scott Sheffield	Math
Mike Sipser	Math
Roy Welsch	Sloan, ORC, ESD

Committee Staff

Tanya Abikoff	SOE

Table of Contents - Statistics

1. Introduction

There is great interest in the MIT community in establishing a program in statistics. Statistical research and statistical practice are being actively pursued throughout MIT in many departments and laboratories.

These existing courses and research programs can be used towards constructing Ph.D., Masters and undergraduate degree programs.

When compared with peer institutions, the elements for building a Ph.D. program in statistics are already present at MIT. A central piece is a core course sequence in probability theory, statistics and data analysis to anchor Ph.D. training in statistics. The course in statistics should emphasize classical statistical theory, high dimensional data and machine learning theory. The data analysis course will be important for teaching the culture of statistical practice and statistical reasoning.

Statistics faculty must be hired to oversee the formulation of the program and direction of these courses.

An undergraduate minor in statistics can be developed right away using existing courses. This minor can be the precursor to a designing an undergraduate major in statistics. Making statistics a required course for MIT undergraduates should be considered.

A Masters program in statistics should also be an immediate priority for the new Entity. The course program for the Masters degree can be developed using the rich array of courses already being offered at MIT.

The Ph.D. program in statistics should be developed after statistics faculty are hired, so that the critical mass of statistics faculty is present at MIT.

Committees will need to be formed to plan the hiring of new faculty and to begin curriculum design.

2. Charge

Statistics is the science of making decisions under uncertainty using principles and models from probability theory and formal data analysis procedures. The need to analyze data to make informed decisions pervades every aspect of society. Although the need to think formally about how to use data properly to make decisions is a long-standing issue, the importance of fostering widespread training in and use of statistical reasoning has become more compelling with the advent of the Big Data era. Every day MIT scientists, engineers and economists solve challenging data analysis, computational and statistical inference questions across a broad range of important problems. As a consequence, much of the infrastructure needed to establish an integrated program in statistics at MIT is already in place. Such a program could create synergies among presently disconnected efforts. Moreover, a statistics program at MIT would uniquely position the Institute to shape the practice of and the training in statistics worldwide. To lay the groundwork for establishing a statistics effort at MIT, Ian Waitz, the Dean of Engineering, has established a faculty Committee with the following charge.

- Assess the breadth of research in statistics being conducted across the five schools at MIT
- Catalog the current educational programs available in statistics at MIT
- Define the important opportunities for research in statistics in society
- Define new opportunities for developing research and education in statistics at MIT
- Define a framework for setting up a statistics program at MIT

3.Statistics at Peer Institutions

The Committee surveyed the statistics departments at several peer institutions considered to be leaders in the field. These were Berkeley, Columbia Cornell, Harvard, NYU, Princeton and Stanford.

Berkeley

The Department of Statistics in the University of California at Berkeley is one of the most respected in the country. The Department is noted for its contributions to the development of classical hypothesis testing and inference. Today the Department has strong links with Computer Sciences and Electrical Engineering. Several of the Statistics faculty have joint appointments in other departments. The core curriculum for the Ph.D. program in Statistics is based on a two course sequence, one in probability theory and one in statistics. Berkeley has just established a Center for Data Sciences as part of a consortium award from the Moore and Sloan Foundation to Berkeley, NYU and University of Washington.

Columbia

Columbia University has one of the oldest statistics departments in the world. Started as a program in statistics in 1931, it was converted to a department in 1946. The interest in statistics as well as funding was fueled by military applications back then. The department underwent some turbulent times in 1960s and 1970s when the school was considering merging it with the existing departments. Looking closely, it appears that the reasons for these troubles was not to do with stagnation of statistics as a research area, but with the fact that several key figures in the department were considering attractive offers in other places. Being traditionally a small department, loosing even a handful of people puts its existence into jeopardy.

Today the department consists of 27 faculty, 15 of which are junior. The department works closely with the Institute for Data Science and Engineering (IDSE) and a lot of research is related to Big Data and applications. It also works closely with other departments such as computer science, operations research and industrial engineering, biology, economics and political science. Jointly with IDSE, the department offers an impressive array of scholarly and professional degrees and certificates. It appears that the demand for these programs is very significant, partially fueled by large concentration of financial institutions in New York. The department jointly with other units also offers a broad variety of research seminars and is associated with several research centers. In summary, Columbia is one of the most vibrant places in the statistics area in the world.

Cornell

Cornell recently established a Statistics Center. The department was initially a "virtual" department, meaning that the faculty all belonged to another formal department at Cornell. It then evolved into a "real" department with 5 faculty members, 3 lecturers, 2 visiting faculty, and another 21 members (all faculty) with primary appointments in other departments.

There is an undergraduate program, a master's program and a Ph.D. program. The programs focus in four areas: applied statistics, computational statistics, mathematical statistics, and probability. All students take course work in all four areas (e.g. each student would take a year-long sequence in each area). The founding chair and the current chair of the Center are Bruce Turnbull and Martin Wells, respectively. They were already faculty at Cornell when the virtual department was established. The department decided to transition from "virtual" to "real" with 5 tenure track faculty lines because they found that a virtual department was not sufficient

Biometry, OR and Economics are primary foci. They do have machine learning, but only one person. There is an absence of strong engineering – long scale systems, scientific robustness, etc. There is industrial engineering in OR, but not a large presence in the department.

Harvard

The Harvard Statistics Department, established in 1957 by Frederick Mosteller, has been an important contributor to statistics over the years. The Department has always been small with only 2 to 4 professorial level faculty and 3 to 5 junior faculty. The Department has relied on faculty from the Harvard School of Public Health and the Harvard Business School to help round out its teaching faculty. The Department has a core set of graduate courses: Statistics 210 (Probability Theory) and Statistics 211 (Mathematical Statistics). Statistics 220 is a course in data analysis which recently has focused on Bayesian data analysis. Each of these is a semester required course for the graduate students. In the last 20 years a major strength of the Department has been Bayesian statistics.

The Department has an undergraduate concentration in statistics which is based on a three course sequence of Statistics 110 (Probability Theory) and Statistics 111 (Statistical Theory). During the last several years the Statistics Department has taken a greater role in undergraduate teaching of statistics throughout Harvard. There are three different introductory statistics courses: social sciences, economics, and biology/medicine. In addition there are a number of undergraduate programs that allow undergraduate minors in statistics. In addition it is also possible for undergraduates who accept sophomore standing to complete a BA/MS in statistics.

NYU

Statistics is one of the three groups in the Department of Information, Operations, and Management Sciences. This department has Information Systems, Operations Management and Statistics with Ph.D. programs in all three areas. The Statistics Department is the smallest of the three, with 8 faculty members. The statistics Ph.D. program is small. Much of the broader statistics related courses are taught in the Information Science and the Operations and Management Departments, the Biostatistics Department and more broadly in the new Data Science Institute at NYU.

The Biostatistics Department, situated in the Department of Population Health, has 10 faculty members and an active Ph.D. program. Much of the probability and statistics courses are provided by the Courant Institute, which has a series of courses in probability and statistics. Most are probability courses, though there are some statistics courses at the undergrad level. Probability theory is particularly strong in Courant.

More broadly, there is a new Center for Data Science at NYU, which looks to be well funded and growing. The Center for Data Science was just established by a grant from the Moore and Sloan Foundations as part of a consortium award to NYU, Berkeley and University of Washington. There are three groups that apply statistics: The Center for Data Science, the Center for Urban Science and Progress (CUSP) and the Center for the Promotion of Research Involving Innovative Statistical Methodology (PRISM). All three offer masters programs. The latter is geared more towards statistics research relevant for social science and econometrics. The Center for Data Science and the Computer Science Department are the homes for the machine learning faculty.

University of Pennsylvania (Wharton School)

The University of Pennsylvania Statistics Department is in the Wharton Business School. There is no other statistics department outside the business school. University of Pennsylvania does have a Department of Epidemiology in the Medical School. As the department sits in a business school, an important responsibility is in teaching the MBA and undergrad statistics courses for Wharton students. In addition to the Wharton responsibilities, the Department also takes on the role of providing statistics courses throughout the university. Undergraduates in engineering often take the Wharton undergraduate statistics course. The department is highly respected for this role. The Department has approximately 15 faculty and 30 graduate students. In the graduate program, the students focus on statistics broadly speaking even though the Ph.D. program is in the business school. The University of Pennsylvania Statistics Department does not have computational machine learning courses. The one taught by the late Ben Taskar was in the Computer Science Department.

Princeton

We specifically studied Princeton because its Department of Statistics was closed in the 1980s. The Department of Statistics at Princeton was founded in the early 1970s with Geoff Watson as the chairman. The other principal faculty members were John Tukey and John Hartigan. John Tukey divided his time between Princeton and being Director of Research at Bell Laboratories. Stuart Hunter was a very well known applied statistician in the Civil Engineering Department and a good teacher. Lack of interest in teaching, personality conflicts and the growing success of Civil Engineering, particularly the area of applied statistics, led to the Department Statistics being closed in the mid 1980s shortly after Tukey's retirement.

Success of Civil Engineering continued with the arrival of Erhan Cinlar from Northwestern who developed strengths in probability, optimization and research through junior faculty hires. The financial industry was growing in the 1990s yet Princeton did not have a presence in that area. A very wealthy alumnus of the Economics Department, Robert Bendheim, wanted to invest in a Center for Finance within the Department of Economics. Cinlar persuaded the then Chairman of the Economics Department, Ben Bernanke, that Probability, OR, and Statistics would be essential for such a Center and together they persuaded the Princeton administration to start a new department within the School of Engineering called Operations Research and Financial Engineering (ORFE) around 2000.

ORFE is now a very strong Department covering probability, statistics, optimization, financial mathematics, machine learning, and operations research. There are undergraduate, Master's, and Ph.D. programs in ORFE and these programs can have a strong emphasis on Statistics. Discussions are going on now about starting some form of separate and more visible program, center, or institute for statistics.

Stanford

Stanford has a strong Department of Statistics. It is considered by some as the best in the country. Many of the applied probability courses taught at MIT are in close proximity to the probability courses taught in Statistics. At Stanford all statistics graduate students take the 300 courses (Statistical Theory) and 310 courses (Probability Theory), each of which takes a full year. The third course in the 300 series, 300C, treats high dimensional data, graphical models and learning theory. Stanford has a large list of

200 level courses, which are intended as master's level courses. Undergraduates can take these courses as well.

Stanford students have a consulting program in which the graduate students are available for anyone from the university to come in for free to receive coaching (e.g. "my paper was rejected because it wasn't statistically rigorous enough," etc.). This is a service to the university, and the students are paid for the time they spend in the consulting center. The department has a beautiful building and they have found that the power of architecture has brought people together. This has helped make the Department a success.

Most of the faculty members in the Department of Statistics have joint appointments. The connection between Statistics and EE at Stanford is particularly strong and in fact, several faculty from EE are joint with Statistics. There are many joint seminars. Stanford also has Wing Wong, who is one of the small number of statisticians who actually runs a laboratory and does experiments in addition to working on methodology. Most statisticians consult or collaborate, so the fact that Wong runs a laboratory and conducts experiments is a unique feature.

At Stanford, there is a reasonable topical overlap between Statistics and Management Science and Engineering (MS&E). Other than a strong intellectual exchange between MS&E, Stanford EE, and Stanford Statistics and business school, in topics like financial engineering, stochastic processes, information theory/signal processing, there is little faculty member overlap. The famous failure of Stanford is the "competing information sciences." They have not gotten computer science/machine learning and statistics to talk to each other.

4. Current State of Statistics at MIT

Statistics research and education in statistics is broadly distributed across multiple departments and laboratories at MIT. These departments and laboratories include the Department of Brain and Cognitive Sciences, the Department of Electrical Engineering and Computer Science, the Department of Mathematics, the Department of Aeronautics and Astronautics, the Department of Economics, the Department of Civil and Environmental Engineering, the Department of Mechanical Engineering, the Department of Earth, Atmospheric and Planetary Sciences, the Sloan School of Management, and the interdisciplinary laboratories of CSAIL and LIDS. Below, we provide an overview of statistics in various departments and laboratories, however, we do not claim this to be a complete list.

Brain and Cognitive Sciences

Brain and Cognitive Sciences (BCS) has three faculty members whose research and teaching involve statistics and machine learning: Emery N. Brown, Tommi Poggio and Joshua Tennenbaum. Brown's research focuses on developing statistical methods for the analysis of neural data. He teaches three courses: 9.07 (Introduction to Statistics for Brain and Cognitive Sciences, undergraduate course), 9.272 (Statistics for Neuroscience Research, graduate survey course) and 9.073 (Topics in Neural Signal Processing, graduate seminar). Poggio's research is on mathematical modeling of the visual system, modeling intelligence and applications of machine learning techniques to problems in neuroscience. He teaches a graduate course 9.520, Statistical Learning Theory and Applications. Tennenbaum's research in is the area of computational cognitive neuroscience and he teaches a course on the same topic. Tennenbaum is also a member of the CSAIL faculty.

CSAIL

The Computer Science and Artificial Intelligence Laboratory (CSAIL) is the largest research laboratory at MIT and one of the world's most important centers of information technology research. Many PIs at CSAIL are using and further developing machine learning and statistical methods in applied contexts. The principal areas of application are: robotics, medical informatics, computational biology, computer vision, natural language processing, and cognitive science. CSAIL also has people focused on statistical methods from a more theoretical perspective, including Konstantinos Daskalakis, John Fisher, Piotr Indyk, and Tommi Jaakkola who are primarily associated with CSAIL, and Ankur Moitra, Cynthia Rudin, Devavrat Shah, and Alan Willsky who are affiliate members with primary affiliations elsewhere.

Machine learning involves computation, algorithms, and representation in addition to probability. As a field, it overlaps strongly with modern statistics. Machine learning and statistical inference are taught by CSAIL faculty at both undergraduate and graduate levels, including 6.036 Introduction to Machine learning (undergraduate, 250+ students), 6.867 Machine Learning (graduate, 150+ students). A number of undergraduate and graduate courses are offered at the interface of machine learning, statistics, and applied areas cited above.

LIDS

The Laboratory for Information and Decision Systems (LIDS) is an interdepartmental research center committed to advancing research and education in the analytical information and decision sciences, specifically: systems and control, communications and networks; and inference and statistical data processing. LIDS offers a wide array of courses in statistics, probability theory including Applied Probability (Basic, Advanced) – 6.041, 6.436, 6.265/15.070; Applied Statistics (Aero Astro); Statistical Inference and Graphical Models – 6.437, 6.438; Information Theory/Communication/Coding; Control/System Identification and; Convex Analysis/Optimization. LIDS offers a number of seminars which cover problems in signal processing, Big Data and machine learning.

Economics/Econometrics

The Econometrics group in the Economics Department consists of 5 members (J. Hausman, W. Newey, J. Angrist, A. Mikusheva, and V. Chernozhukov). Econometrics is an intersection of mathematical statistics and economics. The Econometric Society established in 1933 is a formal organization that supports this area and also publishes journal *Econometrica* (h-5 median impact factor 120). The group teaches 3 undergraduate courses in statistical and econometric methods (14.30, 14.32, 14.36), and also offers 6 graduate statistics/econometric courses (14.381, 14,382, 14.384, 14.385, 14.386, 14.387). Some of the courses have large enrollments (for example, about 50 graduate students take 14.387). The group regularly produces doctoral students who have taken econometrics jobs in top departments (Harvard, Chicago, Stanford, etc.) The Econometrics group is formally ranked as 1 by the *U.S. News World Report* (and the department overall is also ranked as 1 in Economics). The former members of the econometric group include Daniel McFadden and Rob Engle, the recipients of the Nobel Prize in Economics. For the past 30 years, the group holds very active weekly Econometrics seminars jointly with Harvard. They are well attended by faculty from the entire greater Boston area.

Mathematics

The MIT Mathematics Department offers several high-enrollment courses in probability and statistics. These include: 18.05 Introduction to Probability and Statistics (50students/yr); 18.440 Probability and Random Variables (350 students/yr); and 18.443 Statistics for Applications (100 students/yr).

The course 18.443 (Statistics with Applications) is more traditional. There is also 18.445 (Stochastic Processes). 18.175 (Introduction to Probability Theory) is a graduate course that is the analog of Stanford's 310a/b/c. 18.176 is stochastic calculus from a general perspective for finance. There is also a graduate statistics course (18.466), which is the closest MIT has to the Stanford Statistics 300 series and the Harvard Statistics 211 series. The undergraduate probability and statistics course is 18.05.

Mechanical Engineering

In Mechanical Engineering, statistics is distributed widely, but is most concentrated in Design, Manufacturing, and Ocean Engineering. Prof. Dan Frey leads a group on Experimental Design within the MIT/SUTD International Design Center and also co-teaches the main subject in course 2 responsible for providing a foundation in statistics – 2.086. Prof. David Hardt often engages with statistics as part of manufacturing process control and also teaches a statistically intensive subject key to many Master's programs – 2.830. Prof. Franz Hover deals with statistical challenges arising on ocean contexts related to control of distributed systems and optimizing capacity-constrained acoustic communication channels. Hover also teaches a subject covering statistics and random processes for distributed control in the face of such perturbations as ocean waves.

Earth, Atmospheric and Planetary Sciences

In EAPS, there is an ambitious effort called the Climate Modeling Initiative led by Prof. John Marshall. CMI's approach draws together elements of computational fluid dynamics, statistics, meteorology, oceanography and computer science.

Civil and Environmental Engineering

In CEE, there are a variety of research and teaching efforts related to statistics. For example, Prof. Pedro Reis leads the Elasticity, Geometry, and Statistics Laboratory. This laboratory is focused on the failures of structures and materials, which often must be characterized statistically. Daniele Veneziano has research interests in Risk Assessment for Engineering Systems and Stochastic Hydrology and Geomorphology. Prof. Veneziano also teaches one of the most popular subjects that introduces statistical methods for engineering – 1.151 (Probability and Statistics in Engineering).

Aeronautics and Astronautics

In Aero/Astro, statistical methods find a home at the intersection with LIDS. In addition, Aero/Astro faculty members affiliated with the Center for Computational Engineering are engaged in the development and application of statistical methods, primarily in computational Bayesian statistics for large-scale systems (e.g., systems governed by partial differential equations). Researchers in the Aero/Astro Man Vehicle Lab use statistical methods, particularly in the context of experimental design and data analysis.

Sloan School of Management

Statistical methods are used widely in management applications, so topics in statistics appear in many courses offered at Sloan, both at MBA level and Masters and PhD courses. In addition Sloan has several faculty who are statisticians who belong to the Operations Research and Statistics group. Three statisticians in this group include Roy Welsch, Arnie Barnett and Cynthia Rudin. Roy Welsch is specialist in a wide range of statistical topics, including methods of statistical robustness. Arnie Barnett is specializing in applications of statistics in many areas, specifically aviation safety, health care and law enforcement. Cynthia Rudin is a machine learning expert working in the area of boosting methods and their applications. In addition several operations research faculty work in statistics related areas such as learning theory and optimization methods in statistics, including convex optimization and integer programming methods. Another important area is finance and quantitative marketing.

From these various schools and departments, we have a reasonable set of courses covering aspects of statistics (listed below), but not much organization. The MIT Master's Degree in Computation for Design and Optimization (CDO) is an example of an interdisciplinary degree program. CDO is administered by the Center for Computational Engineering, a virtual center involving faculty members from across the Institute. The structure of the CDO degree might prove a useful model on which to base a master's degree in statistics.

Partial Listing of Statistics Courses at MIT

1.010	Uncertainty in Engineering
1.151	Probability and Statistics in Engineering
1.202J	Demand Modeling
1.69	Introduction to Coastal Engineering
2.017J	Design of Electromechanical Robotic Systems
2.086	Numerical Computation for Mechanical Engineers
2.22	Design Principles for Ocean Vehicles
2.671	Measurement and Instrumentation
2.830	Control of Manufacturing Processes
6.036	Introduction to Machine Learning
6.436/15.085	Fundamentals of Probability
6.867	Machine Learning
9.07	Introduction to Statistics for Brain and Cognitive Sciences
9.073	Statistics for Neuroscience Research
9.272	Topics in Neural Signal Processing
9.520	Statistical Learning Theory and Applications
12.012 / 12.444	MatLab, Statistics, Regression, Signal Processing
12.515	Data and Models
12.714	Computational Data Analysis
14.30	Introduction to Statistical Method in Economics.
14.32	Econometrics.
14.36	Advanced Econometrics.
14.381	Statistical Method in Economics.
14.382	Econometrics: Regression Analysis.
14.384	Time Series Analysis.
14.385	Nonlinear Econometric Analysis.
14.386	New Econometric Methods.
14.387	Topics in Applied Econometrics.
15.062	Data Mining
15.064	Engineering Probability and Statistics (summer)
15.068	Statistical consulting
15.070	Advanced Stochastic Processes
15.075	Statistical Thinking and Data Analysis
15.077	Statistical Learning and Data Mining
15.097	Prediction: Machine Learning and Statistics
15.098	Special Seminar in Applied Probability and Stochastic Processes
16.09	Statistics and Probability
16.391J	Statistics for Engineers and Scientists
16.470J	Statistical Methods in Experimental Design
17.800	Quantitative Research Methods I:Regression
17.802	Quantitative Research Methods II: Causal Inference
17.804	Quantitative Research Methods III: Generalized Linear Models and Extensions
17.806	Quantitative Research Methods IV: Advanced Topics
18.05	Introduction to Probability and Statistics
18.175	Probability Theory
18.440	Probability and Random Variables
18.443	Statistics for Applications
18.465	Topics in Statistics
18.466	Mathematical Statistics

5. Core Statistics Curriculum

The essential elements for setting up a program in statistics at MIT are establishing the core curriculum. We have learned from surveying our peer institutions that the basic components of this core curriculum are three graduate courses: Probability Theory, Modern Statistical Theory, and Data Analysis. These courses will provide essential elements for establishing the culture of statistics at MIT. The key characteristics of this culture are teaching: 1) how to reason under uncertainty; 2) the principles of statistical model construction; and 3) the principles of statistical model criticism. Recruiting statisticians to the MIT faculty will be crucial for establishing and maintaining this culture. The committee recommends also creating stat.xxx classification of the existing and future statistics related courses, so that the students can easily navigate which MIT courses qualify for various statistics requirements. In light of the fact that these courses are dispersed among many departments at MIT, it is important that such a classification is available.

Probability Theory

The topics in this course should include probabilistic axioms based on measure theory, , weak and strong laws of large numbers, central limit theorem, modes of convergence, large deviations bounds and concentration inequalities, theory of Markov chains and Markov processes, and martingales theory. This material is currently covered in 15.085, 15.070 and 18.175. Model for how to make these courses relevant to statistics are Statistics 210 at Harvard and the Statistics 310 series at Stanford.

Modern Statistical Theory

The modern statistical theory course should be a two-semester course in which the fundamentals of classical statistics and modern statistical theory are covered. The topics should include; families of distributions, estimation theory including likelihood theory, asymptotic theory, decision theory, Bayesian theory, robust estimation, and minimax theory. Much of this material is covered in 18.466. Other topics should include hypothesis testing, analyses of large data systems and modern learning theory. The objective of the course is to make the graduate students well rounded in the established paradigm for constructing statistical procedures and evaluating their properties. A model for this course is the Statistics 300 series at Stanford.

Data Analysis

The data analysis course will be a topics course that covers 4-6 major areas of statistical applications with the objective being to bridge the gap between theory and conducting practical applications in real world problems. The course would be taught following the Box-Tukey paradigm of iterative model building. The students would be given questions in a topic area and experimental data on the topic and be required to analyze them. Areas of application would be chosen broadly such as political science, economics, the environment, biology, and medical sciences. Courses in each of these areas are currently taught at MIT. A model for this course is Statistics 220 at Harvard.

These courses are crucial defining a statistics foothold at MIT and for establishing the Ph.D. in statistics. These courses should be cross-listed across, say Mathematics, Economics, EECS, Brain and Cognitive Sciences and Sloan. The new Entity must take responsibility for maintaining this core of courses.

6. Undergraduate Minor in Statistics

With existing courses at MIT it will be easy to define an undergraduate minor in statistics. Options, such as EE/Stat, CS/Stat, Econ/Stat, Math/Stat, BCS/Stat, Biology/Stat and Management/Stat can be easily defined. These minors serve as a basis for setting up an undergraduate concentration in statistics, which, like the Ph.D. program in statistics, will be run under the auspices of the new Entity. Creating a statistics requirement for all MIT students is a topic that should be considered.

7. Masters Program in Statistics

A Masters program in statistics should also be an immediate priority for the new Entity. The course program for the Masters degree can be developed using the rich array of course already being offered at MIT. It would provide a way to foster cross-disciplinary training.

8. Next Steps

Committees will need to be formed to plan the hiring of new faculty and to begin curriculum design.

9. Summary

There is great interest in the MIT community in establishing a program in statistics. Statistical research and statistical practice are being actively pursued throughout MIT in many departments and laboratories.

These existing courses and research programs can be used to construct Ph.D., Masters and undergraduate degree programs.

When compared with peer institutions, the elements for building a Ph.D. program in Statistics are already present at MIT. A central piece is a coordinated core course sequence in probability theory, statistics and data analysis to anchor Ph.D. training in statistics. The course in statistics should emphasize classical statistical theory, high dimensional data and machine learning theory. The data analysis course will be important for teaching the culture of statistical practice and statistical reasoning.

Statistics faculty must be hired to oversee the formulation and teaching of these courses.

An undergraduate minor in statistics can be developed right away using existing courses. This minor can be the precursor to a designing an undergraduate major in statistics. Making statistics a required course for MIT undergraduates should be considered.

A Masters program in statistics should also be an immediate priority for the new Entity. The course program for the Masters degree can be developed using the rich array of course already being offered at MIT.

Report on Organizational Structure

Committee Co-Chairs

Anantha Chandrakasan	EECS
Alan Willsky	EECS, LIDS

Committee Members

Markus Buehler	CEE
Arup Chakraborty	IMES
Munther Dahleh	EECS, LIDS, ESD (ex officio)
Melissa Nobles	Political Science
Jaime Peraire	AA
Donna Savicki	SOE
Yossi Sheffi	ESD
Mike Sipser	Math
Victor Zue	EECS, CSAIL

Committee Staff

Brian Tavares	SOE

Table of Contents – Organizational Structure

1.Introduction

Dean Ian Waitz of the School of Engineering (SoE) created four committees to examine the key issues associated with the creation of a new entity envisioned to incorporate a new research and educational effort in statistics, activities currently in the Engineering Systems Division (ESD), the Laboratory for Information and Decision Systems (LIDS), and other individuals and activities associated with socio-technical systems. Our committee was charged with examining issues related to the organizational and operational structure of the proposed new entity. Our complete charge is included as Appendix A to this report, and the members of the committee are listed in Appendix B. The Committee held a series of meetings to discuss the key issues and also met with various individuals and groups (see Appendix C) whose activities and interests overlap with those of the proposed new entity. This report summarizes our recommendations.

Our committee received some initial guidance from Dean Waitz, however, he encouraged us to debate these points and recommend whatever we feel is best:

- All existing allocation accounts should be preserved. This refers to LIDS, the Sociotechnical Systems Research Center (SSRC), and the Center for Transportation and Logistics (CTL).
- ESD will not continue as an independent entity, reporting to the SoE. Rather, its mission, programs (research, service, education) are to be integrated within the new entity or, if recommended, into other units at MIT.
- SSRC should be integrated into the new entity but potentially repurposed and augmented to provide strong leadership in socio-technical systems.
- LIDS will continue as a laboratory within the new entity and will provide leadership in the information and decision sciences.
- There is a strong preference to have all faculty associated with the new entity have their appointments through existing departments.

After discussing, debating, and seeking input on these and many other topics, we recommend an organizational structure consistent with this guidance. We also recognize that what we propose here is an initial condition for the new entity. As this is a new entity and as there are other subcommittees (notably those on statistics and on educational programs) whose recommendations are being prepared in parallel with ours, we fully expect that as this new entity stands up and evolves, there are almost certainly going to be corresponding changes in structure beyond those described here. In anticipation of these inevitabilities, we strongly recommend an initial structure that is flexible so that changes can be easily effected.

2. Recommendations

Initial Structure of the New Entity

The following recommendations should be viewed as the initial conditions for the structure of the new Entity. This structure may be re-evaluated and changed based on the Entity's experience after launch. Our recommendations for the initial structure of the new entity are as follows:

- The Director of the new entity have the authority to create a Steering Group and appoint Associate Directors in a manner best suited to fulfilling the mission of the entity.
- The Director and the Steering Group will have the responsibility for developing and managing the integrative functions and initiatives that are essential to the vision for the entity. These include:
    - Oversight and management of all academic programs associated with the entity
    - Fostering, developing, and managing major research initiatives that cut across not only the units within the new entity but also other units across MIT
    - Coordinating and developing professional and industrial outreach that again cuts across unit boundaries
    - Coordinating all activities on search, hiring, and promotion
- Our recommendation for the initial Steering Group is that it consist of:
    - The Director of SSRC (potentially renamed as it is repurposed and augmented)[1]
    - The Director of LIDS
    - The Director of the new Center for Statistics[2]
    - An Assistant Director for Administration for the Entity
- CTL is a tightly integrated, highly successful unit with strong interrelated components of education, research, industry ties, and international programs. We also note that in most other schools logistics and supply chain management are parts of management faculties.
    - We recommend that CTL continue as a unit as it is now (including as an allocation account) but not report to the new entity.
    - CTL currently reports to the SoE. It is recommended that CTL continue to report to the SoE as a unit while building stronger connections to the SOM.
    - CTL should still get its PhD students from the new entity and the director would still be a member of the new entity
- The committee strongly recommends that the two allocations accounts (LIDS and SSRC) within the new entity continue. It is expected that research contracts within the new entity will be run through one of these units.
- Recognizing that the vision for the new entity involves connections to and contributions from faculty in all of MIT's Schools and many departments, we recommend that the entity report to the SoE, with dotted line to the Deans of the five Schools
    - If the balance of effort within the entity shifts (e.g., due to faculty distribution among departments, focus of the entity, the entity's leadership), we recommend that the option be kept open for the entity to report to a different School.

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[1] For specificity we will use the existing acronym SSRC in this document.

[2] We recognized that the committee charged with examining statistics may have a different name for this unit. For specificity we will refer to it as we do here.

- All faculty, current or those future hires associated with the slots that have been committed to the entity, will have their appointments through departments, with the possible exception of some existing ESD faculty (as explained subsequently)
- The Committee recognizes that there are a number of other units whose intellectual agendas overlap significantly with the proposed mission of the new entity.
    - We recommend that the new entity form an Advisory/Liaison Board, including research leaders from these other units in order to ensure that the units work collaboratively, especially on cross-cutting research programs, to the benefit of all.

Membership of the New Entity

With regard to membership in the new entity and the interactions with departments on search, and promotion, we have the following recommendations:

- We recommend that there be two categories of membership in the new entity, namely Core and Affiliate members.
- With regard to the transition of current ESD faculty, we have the following recommendations:
    - ESD faculty (either 100% or 50% duals) will negotiate with departments and the Director of the new entity to become part of a department and how to be affiliated with the new entity. ESD faculty will also have the option of reporting to the Director of the new entity if necessary, although they will officially be on the rank list of the SoE, as the entity will not officially hold faculty slots
    - If a current ESD junior faculty member chooses to report to the Director of the new entity, his or her promotion cases will be led by the Director of the new entity, who will present the case to Engineering Council
    - ESD joint faculty will each discuss their future involvement with the director of the new entity.
- With regard to core members, we have the following recommendations:
    - It is expected that all current members of LIDS and new hires will fit in this category, as will any current ESD faculty whose discussions with the Director of the new entity lead to their electing this option.
    - It is also possible for an individual to be a core member without belonging to one of the units within the new entity.
    - Contracts for core members can be run through any DLC. However, this should be balanced by the members resident in the allocation account units within the new entity in order to maintain the required level of allocation funds.
    - It is expected that core members will be actively involved not only in research aligned with the mission of the new entity but also in service and related activities (search, entity colloquia, industrial outreach, ...).
    - It is also expected that the teaching of core members will be well aligned with the entity's mission.
        - However, we recognize the need for this to be balanced by the educational needs of the home department of each core member and recommend that the teaching responsibilities of any core member involve a 3-way negotiation among department, entity director (and, where appropriate, unit leader), and the faculty member on both expected teaching and service duties to the new entity.
        - For a current faculty member who is core to the new entity, we expect there to be alignment of the member's teaching with responsibilities to both department and the

        new entity, recognizing that any teaching in the new entity also serves the needs of the department. This is roughly equivalent to cross-listing of courses for most faculty members.
  - For new hires, there is the expectation that they will contribute 50% teaching in the new entity (analogous to a teaching dual).
    - As discussed subsequently, the explicit intent of any search for a new hire associated with the new entity and with a particular department is that the person sought would be in an area aligned with the strategic plans of both the new entity and the department. This implicitly represents a commitment by the entity, department, and new hire to negotiate teaching responsibilities that are consistent with the intellectual agendas of all three.
- We also recommend that any department can choose to be a member of the new entity if it finds that the mission of the new entity is well-aligned with the its strategic plan
  - We would then expect that such a department would be directly involved in setting objectives and other activities of the new entity, including the definition of strategic hiring directions (see discussion to follow).

Faculty Search Process

With regard to the faculty search process for a hire for one of the slots available to the new entity, we have the following recommendations:

- The new entity will initiate each year's search by defining strategic hiring areas (e.g., statistics, network science, …). This will be the responsibility of the entity Steering Group.
- These areas will be discussed with departments at the start of the search process in order to identify a department whose intellectual agenda and needs match with each search identified by the Steering Group. This, and the subsequent parts of this recommendation are crucial to ensuring host department "buy-in" to any potential hire.
  - Any department that has become a member of the new entity will be involved in this automatically as part of the setting of strategic directions
- The entity's search committee will include strong representation from the appropriate departments, including participation from departments that are members of the new entity.
- We expect that candidates for these slots may come in two ways:
  - The entity search committee identifies top candidates and brings them to the attention of the relevant departments.
  - Departments identify candidates from their searches for possible consideration by the new entity.
- We recommend that candidates identified in either of these ways be interviewed by both the entity and the department (this can be accomplished with a 3-day interview).
- Any decision to go forward with a hire will require support from the department in which that hire would reside.

  Slots allocated to the entity should be flexible: E.g., SoE slots don't necessarily go back to SoE departments, as the entity should be able to hire the best candidates to realize its mission.

The institute will also be able to hire PoPs, Visiting Professors, and Adjuncts hired directly into the new Entity. This provides flexibility to carry out the required mission of the institute.

Review and Promotion for Core Members

With regard to review and promotion for core members, we recommend the following:

- The Department Heads and entity Director will work together to perform the annual review of core members of the entity.
- The DHs and entity Director will work together to create a list of letter writers and jointly solicit the promotion letters.
- The DHs and entity Director will work together to prepare cases.
- The Entity Director (or a designated associate director) will participate in all the pertinent promotion cases in their entirety in Engineering Council, if the Entity has a similar case in that cycle; otherwise, the Director will not participate.
- For the schools other than SoE, the entity Director may attend the school council if invited by the DHs and with approval of the corresponding Dean.

Financial Structure and Resources

With regard to financial structure and resources, we recommend the following:

- The new entity is intended to be a driving force in areas of central importance for MIT and for society. Sufficient resources will be needed to achieve the success envisioned in the mission of the new entity.
    - We recommend that funds to support this mission be part of the upcoming capital campaign.
    - Of particular importance in the first few years of this entity will be funds to support start-up packages for new faculty. While we expect that home departments of these new hires will contribute to these packages, we also believe that one of the key responsibilities of the Director should be to work with others at MIT to identify and raise these resources.
- With regard to GIB funds, we recommend that the GIB to support current faculty who become core members of the new entity, as well as new hires, reside in the departments where the faculty members' appointments reside.
- The portion of funds budgeted for faculty members on sabbatical or on leaves without pay that are not customarily scooped by the Institute or the Dean's office will be distributed between department and the new entity in a fair fashion when it is applicable. This will be negotiated on a case-by-case basis.
- The units that currently exist and that will be affected by the creation of this new entity have administrative support provided by various sources (e.g., the LIDS Director and the LIDS Director's Administrative Assistant are paid from the Lab Directors account, which is under the control of the VPR). We expect that one of the first responsibilities of the new entity Director will be to provide a detailed picture of existing administrative resources in units associated with the creation of this new entity and any re-allocation of any of those resources and any additional resources that may be required (e.g., for an administrative lead for the Center on Statistics).

Allocation of Space

The final major challenge that we address here is that of space. We recognize that this is a difficult issue, given the geographic distribution of the units envisioned to be involved, either completely or in part, in this new effort, as well as the needs for space associated with the slots that have been allocated to the new entity. Rather than recommendations, we provide several considerations that need to be taken into account in the allocation of space required for the success of this new entity:

- Our rough estimate of the total space requirements for the new entity is based on simple arithmetic. There are approximately 18 faculty slots that have been identified for the new entity, beyond the number associated with LIDS, which houses essentially that number of faculty as well. Thus a starting point for total space associated with the new entity is roughly twice the size of the space allocated to LIDS. However, we emphasize that this is just a starting point for space discussions, as there are certainly several crucial issues that can lead to adjustments to this number. Among these are:
    - The space needed for any component of any of the professional masters programs that remain within the entity. We note that at present some space assigned to ESD is co-associated, while much of the space for these programs is provided externally to ESD space.
    - The creation of a headquarters for this new entity and for the Center on Statistics. Whether this requires space beyond the "two times LIDS" number is something that we believe the new Director needs to determine and present to MIT senior administration.
- We recognize that in the ideal situation, the entity would have a centralized and cohesive geographic footprint. We also recognize that some geographic separation is inevitable. For example, a requirement for LIDS to participate in this new entity is it does not relocate.
- However, we recommend that every effort be made to identify a cohesive and centralized location for space for new faculty and for the headquarters of the entity and the Center for Statistics.
    - We recognize that the allocation of space for any new hire must also take into account the needs of the department that will be the academic home of that new hire.
    - We also note that some of the new hires will likely work in areas and have intellectual footprints that match up well with LIDS. As such, LIDS will be a natural "home" for such hires, perhaps located in entity space beyond the current footprint of LIDS.
- Understanding the current situation of space allocated to individuals and units that would be affected by the creation of this new entity is not difficult for LIDS but is more complex for ESD, thanks in part to the interaction with professional masters programs and to some of the space associated with CTL. One of the important initial responsibilities of the new Director will be to provide an assessment of space that is available for the new entity now (e.g., all LIDS space and those parts of ESD space corresponding to individuals and activities that will become parts of the new entity) and then to present a complete space proposal to MIT administration that addresses space changes and needs consistent with the considerations we have outlined.

3. Appendices

Appendix A – Charge to the Committee on Organizational Structure

The overall charge to this committee is to provide recommendations for an effective organizational structure of the proposed entity[3] and its organizational relationships to other units at MIT. The issues to be addressed by this committee and the recommendations to be formulated include:

- Working collaboratively with other committees, identify the units that report directly to the new entity, including both existing and new units; propose the mapping of existing programs and people into these units.
- Defining the organizational structure of the new entity and how the units reporting relate to it organizationally. This includes recommendations on:
    - Administrative issues, including cost center structure, contract management, IT support, and administrative and support staff. This includes the financial and administrative structure of new units within the entity (e.g., center on statistics). This should consider the constraints that some departments (e.g., EECS) don't offer contract management. Also central to this part of the charge are recommendations on centralization vs. decentralization of these functions and staff and the mapping from the current structures of the existing units to be included in the entity to the proposed administrative structure.
    - Leadership structure, including the relationship of the leaders of the individual units to that of the overall new entity and the distribution of responsibilities and authority between the overall entity and the units that comprise it. Assess the pros and cons of alternative leadership structures based on functions rather than units.
    - Space structure and management, including assessment and recommendations concerning the space occupied currently by units to be included in the new entity, additional space needs and preferred locations for proposed new units, the space needs and locations for new faculty hired in to the new entity as well as for their students, and the location of the official "home" and headquarters of the new entity. Of particular concern here is the consideration of space issues in relation to the objective of fostering collaborations across the new entity.
- Making recommendations for the interactions of the entity and its members with other units at MIT. This includes:
    - Identifying and codifying the meaning and expectations for "layered" membership within the new entity, including teaching duals, core, and affiliate members, as well as specifying the process for members of other units joining the new entity (including recommendations on the issue of whether all those associated with the new entity

[3] For the purposes of this document, the word "entity" refers to the proposed overall new organization, while the word "unit" is used to refer either to existing or proposed new units, both to be included in the new entity and outside of it but with interacting the new entity.

must be members of one of the units within it or whether there may be "at large" members within the new entity.).

- Recommendations for interactions with Departments on teaching duals, including the alignment of interests to reflect each departments teaching needs as well as the overlap in those needs and those associated with the new entity, as well as consideration of the impact of these recommendations on the allocation of funds from the GIB. The group should articulate the impact on department engagement for faculty choosing a teaching-dual role with the new entity.
- Guidelines for the allocation of financial resources (e.g., teaching replacement funds, support for administrative support, TA allocation, etc.) must be developed. Recommendations on the contribution to the startup funds from the new entity for new hires should be clearly articulated.
- Recommendations on interactions with departments on hiring, including the structure of search committees and the decision process. The committee will propose multiple models recognizing the different ways schools allocate slots.
- Recommendation on the overall promotion and tenure process should be outlined including the involvement of the director of the new entity in preparing and presenting the promotion cases. The setup of IMES should be used as a starting point for both promotions and faculty search.
- Interactions with other non-departmental units with research and/or educational domains that overlap with the new entity. This includes any explicit methods for coordination to enhance collaboration and a process for coordinating on affiliations for new hires.

Appendix B – Committee Members

Prof. Markus Buehler

Prof. Arup Chakraborty

Prof. Anantha Chandrakasan (committee chair)

Prof. Munther Dahleh (ex-officio)

Prof. Melissa Nobles

Prof. Jaime Peraire

Ms Donna Savicki

Prof. Yossi Sheffi

Prof. Michael Sipser

Mr. Brian Tavares (committee administrative lead)

Prof. Alan Willsky (committee co-chair)

Prof. Victor Zue

Appendix C – Individuals/Groups with Whom the Committee Met

The following is a list of individuals and groups with whom meetings were held to gather input:

- Chair, Dept. of Brain and Cognitive Sciences
- Department Leadership Group and Personnel Committee of the Dept. of EECS
- *Chair, Dept. of Economics – Meeting to be scheduled*
- Deans: Sloan School of Management, School of Architecture and Planning, and School of Humanities, Arts and Social Sciences
- PIs and Staff of the Engineering Systems Division
- PIs, Administrative staff, and students of the Laboratory for Information and Decision Systems
- Mechanical Engineering
- Faculty, Dept. of Aeronautics and Astronautics
- ESD Students
- CSAIL Cabinet
- Director, Research Laboratory of Electronics
- Administrative Officer, Dept. of Electrical Engineering and Computer Science