California Institute of Technology

Report of the 2019 Visiting Committee
for the
Division of Engineering and Applied Science

March 19-21, 2019

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Polishing the Gem: Observations and Recommendations for Enhancing EAS Excellence

Report of the 2019 Visiting Committee for the Division of Engineering and Applied Science

1. Introduction

The Visiting Committee for Caltech's Engineering and Applied Science (EAS) Division met on campus on March 19-21, 2019. During our time in Pasadena, all 13 members of the Committee participated fully in a series of presentations by and discussions with Institute and Division leadership, department heads and research center directors, undergraduate and graduate students, and post-doctoral scholars. The Committee was very impressed with the uniformly high caliber of EAS's people and their evident enthusiasm about and commitment to the research projects and educational activities underway across the Division.

From our interactions on campus and subsequent remote deliberations, the Committee believes EAS is in a strong position to continue its long-standing tradition of ranking among the world's top engineering institutions and of carrying out path-breaking research in fundamental and interdisciplinary fields, often at the boundaries between engineering and science. We also observe that the Division has made notable progress in implementing the recommendations from its last visiting committee that convened in 2014. However, our Committee noted several important areas – including undergraduate teaching and graduate mentoring, research priorities and focus areas, faculty recruitment and diversity, and strategic planning and funding – where additional opportunities exist for making EAS even better. Therefore, we offer our observations and recommendations in the spirit of "polishing the gem" that EAS has long represented for Caltech and our country.

2. Division Overview

The EAS Division is the largest of Caltech's six academic units, with approximately 24% of the Institute's faculty, 38% of its graduate students, and 58% of its undergraduate students. As indicated in the table below, student interest in EAS degree programs, courses and research has continued to increase in recent years, with about 10% more students now than in 2014 and with a 50%-plus increase in post-doc scholars over the same period. Partly in anticipation of this growth, the Division was reorganized into seven departments in 2010, with Medical Engineering replacing Bioengineering in 2013.

In its educational programs, the Division today administers eight undergraduate majors for B.S. degrees, seven undergraduate minor options, three M.S. degree programs and 14 Ph.D. degree programs. EAS's research activities are classified into seven broad areas and are frequently interdisciplinary in scope, with participation from the Institute's other academic divisions and the Jet Propulsion Laboratory. Beyond smaller-scale (or individual) research programs, EAS is pursuing a range of large-scale programs that are carried out in multi-departmental initiatives and inter-divisional centers.

For the 2018-2019 academic year, EAS's operating budget is approximately $109 million, or about 16% of the Institute's total annual spending of $677 million. Division sponsored research provides about $57 million, endowment returns and gift funding contribute $37 million, and Institute general sources account for $15 million of the budget. During the last five years, EAS's operating budget has increased by 25%, up from $87 million in 2014. (See Table 1).

Table 1. EAS Division Trends (2018 vs. 2014)

	2014	**2018**	**% Change**
Faculty (FTE)	73.5	75.0	2%
Lecturers (FTE)	13.5	16.5	22%
Undergraduate Students	357	390	9%
Graduate Students	441	491	11%
Post-Doc Scholars	78	120	54%
Division Annual Budget	$87M	$109M	25%
Sponsored Research Funding	$46M	$57M	24%

EAS offices, classrooms and laboratories are primarily housed in 12 campus buildings containing 330,000 square feet of space. While the majority of these buildings were constructed or renovated in the last 15 years, several others are more than 35 years old and in need of replacement or major upgrades.

Like the rest of Caltech, the EAS Division is relatively small compared to its peers, as measured by the size of its faculty and number of students. Nevertheless, the Division has consistently ranked among the top five graduate engineering programs, reflecting the high quality of its people and their disproportionate impact on many fields of engineering and applied science.

3. Responses to the President's Charge

President Rosenbaum's charge to this year's EAS Visiting Committee included five specific questions. These questions are repeated below in italics, followed by the committee's observations, suggestions and recommendations about them.

1: The visiting committee report of 2014 raised issues regarding strategic planning, graduate student support, and infrastructure. Have we made progress? Given our size, structure and resources, what can we do to improve our profile and visibility?

Strategic planning. The Committee understands that strategic planning has been on the minds of several previous visiting committees, dating back about 15 years. While it appears the Division has now clearly articulated its core principles and major objectives for research, education, infrastructure and fundraising, we believe several elements of successful long-range integrated planning may still be missing. For instance, in the all-important area of faculty hiring and promotion, the Committee did not perceive that a clear five-year plan exists for what EAS's faculty size and composition are targeted to be in 2024-2025 which, if true, would seem to inhibit well-defined and appropriately paced professorial searches and hiring.

The Committee observes that top scholars in several disciplines (e.g., such as Computing and Mathematical Science and Medical Engineering) are in very high demand. In some cases, Caltech's relatively slow process of opening faculty searches and making professorial offers seems to have put the Division at a competitive disadvantage compared to peer schools. This is one area where an integrated long-range plan would be helpful in allowing for more orderly searches and greater agility in hiring outstanding faculty and lecturers, especially in the under-staffed computer science group.

In addition, our review material did not include information on anticipated budget projections or funding sources for the Division in the coming years. The Committee notes that it is difficult to see how EAS can fully achieve its objectives and meet its obligations with only its current 16% share of the Institute's spending. Similarly, the material lacked a competitive assessment of EAS's strengths, weaknesses and opportunities in its major new research initiatives. It also did not address the process and timeline for phasing out older fields of inquiry to allow the ramp up of new areas in ways that minimize the dilution of intellectual and financial resources. Therefore, while the Division has made commendable progress on long-range planning since the 2014 committee's review, we echo their recommendation for even more systematic planning looking out five-plus years. We also suggest that each department prepare consistent long-range plans for their education and research activities.

Graduate Student Support. Caltech has pursued and, within EAS, largely accomplished the admirable goal of providing endowed fellowship funding for all first-year graduate students and, in selected cases, for second-year students as well. While even greater endowed funding remains a high priority for the coming years, targeting universal full degree coverage should be pursued cautiously, as it could result in unintended challenges with federal agency funding, appropriate allocation of students to research efforts and other problematic outcomes (we suspect this is an Institute-wide issue). The Committee's discussions with EAS graduate students indicated that a related matter of perhaps equal importance is to clearly communicate to prospective and current graduates that, assuming satisfactory academic progress, they will be funded for their full Ph.D. program, whether from endowed sources or other means.

Moreover, while the Division has been very successful in attracting extremely talented students for its Ph.D. programs, it faces significant competitive challenges from top peer institutions. Overall acceptance rates for graduate students average around 40%, but this number masks the challenge that EAS faces in attracting top domestic candidates. As noted below, the split between international and domestic graduate students has been around 60/40 over the last three years. In part, this reflects an acceptance rate for domestic students that is lower than that for international students, with financial support being one of the reasons mentioned by U.S. candidates turning down EAS offers.

On a related point, the Committee noted the disparity between the composition of undergraduate students (91% of whom are from the U.S.) and that of graduate students (57% from overseas) and post-docs (87% international). While we applaud the Division's ability to attract so many exceptional people from around the world, we also worry that increasingly attractive overseas academic and industrial opportunities, along with more stringent U.S. immigration policies, may cause many of these scholars not to remain in this country. Since the vast majority of Caltech's sponsored research funding as well as its philanthropic contributions come from public and private

domestic sources, this situation could become increasingly problematic in the years ahead. Accordingly, we recommend that the Division redouble its efforts to attract highly-qualified U.S. students to its graduate and post-doc programs.

Infrastructure. Since 2014 major progress has been achieved in renovating and modernizing EAS teaching and research facilities. The Committee was particularly impressed with its tours of two of these updated buildings – Gates-Thomas and Karman – and understands that additional upgrades have been completed in Moore and Keck as well. We also compliment the Institute for its new campus-wide construction initiatives that created the Bechtel residence and Hameetman student center that opened in 2018. Looking ahead, it appears that EAS's next large infrastructure investments will be for the renovation or reconstruction of Watson Laboratory and for expanded classroom and research space for CMS.

Regarding the Watson project, the Committee was impressed by the Applied Physics and Materials Science (APhMS) department's vision for its new Quantum Engineering Center (QEC), which has the potential to revolutionize the design of matter, the harnessing of energy and the organization of information. To fully realize this potential, a replacement for Watson should receive serious consideration. Based on preliminary architectural design work, the new building will include two basements and three floors above ground on a similar footprint as the current Watson Lab, expanding its useable space about five-fold. The new building, which is estimated to cost around $150 million, will provide space not only for the QEC and its various labs but for enhanced space for the Kavli Nanoscience cleanroom and teaching laboratories as well. The Committee endorses EAS's plan to proceed with this new facility as soon as appropriate funds are available.

While the Committee did not have time to pursue the matter in any depth, we also note the need for more attractive and affordable housing for graduate students and post-docs is likely to increase in the coming years.

2: The Division reorganized into departments in 2009-2010. In particular, have the Departments of Computing & Mathematical Sciences and Medical Engineering developed appropriately? Can we further leverage the departmental and cross-departmental structure to become more competitive with peer universities and larger schools of engineering? Are there areas of Caltech-style research that are being overlooked? Areas in which investment might be expected to yield especially important returns?

CMS Department. As the largest department within EAS, Computing and Mathematical Sciences' (CMS) 18-member faculty is responsible for the Institute's most popular undergraduate program (with more than 250 sophomores, juniors and senior majors and another 30-plus minors) and the Division's dominant class enrollments (nearly 3,500 combined undergraduate and graduate student course seats in 2018). Adding in its research leadership in fundamental contributions at the intersection of computing and applied mathematics and its collaboration with other researchers across the school, CMS has done a remarkable job of moving Caltech toward the top tier of computer science (CS) institutions, despite starting well back in the pack in the early 2000's and having quite limited resources compared to larger peers.

Today, however, computer science at Caltech faces several significant challenges, with much at stake for both the Division and for the Institute as a whole. Driven by the recent successes in this field – especially machine learning and AI − in industry and across society, most universities are seeing dramatic increases in computer science students and associated research programs. At Caltech, the increase is extraordinarily large; currently more than a third of undergraduate students are majors and about half of all graduating seniors have either a major, a double major or a minor in computer science. Moreover, the challenge is amplified at Caltech since the computer science faculty is quite small and has been unable to expand as contemplated by the 2014 visiting committee. In addition to this academic pressure, there are considerable research demands on the faculty, as computer science has become a foundational tool for advances in other technical areas and, consequently, to the increasing need for their expertise in many research projects throughout the Institute.

Therefore, beyond the specific staffing and related CMS recommendations we discuss on pages 8 and 11 below, the Committee believes that Caltech should strongly consider revising its undergraduate program to include introductory computer science in the core curriculum and to add more advanced upper-class, discipline-oriented CS courses in each Institute division. This would move the current "hub-and spoke" computing model to its logical conclusion and more equitably distribute the educational responsibility for instruction among the divisions, while also strengthening CS-enabled interdisciplinary research across the campus. Furthermore, a systematic advisory program for freshmen and sophomores on the choice of majors and subsequent career opportunities would be very helpful to them in making informed decisions consistent with their intellectual interests that attracted them to Caltech in the first place. However, these changes alone would be unlikely to dramatically reduce the teaching overload in CMS, so our additional suggestions below are still important to consider.

Finally, the Committee feels that Caltech has a real competitive advantage, due to its small size and interdisciplinary culture, to broadly pioneer the applications of machine learning and AI in the basic sciences in ways that transform many physical, chemical and biological disciplines. However, AI-based tools are advancing rapidly and larger peers are investing considerable resources along similar lines, so the Institute needs to move quickly with an expanded AI4 Science campus-spanning research initiatives if it is to maintain leadership in this field.

MedE Department. Advanced medical technologies that arise from multidisciplinary programs of fundamental and translational research have the potential to radically transform existing methods for monitoring, treating and preventing disease. Current and proposed activities seek to exploit Caltech's singular strengths in materials science, applied physics, mechanical engineering, electrical engineering and other traditional fields of applied study, leveraged with a distinguished record of innovation in micro/nanoscale technologies, photonic components and electronic/optoelectronic devices. A unique defining feature of this program is its rigorously application-based approach, oriented around unmet clinical needs and societal impact, and built on a strong foundation of academic engineering science.

The department that serves as the centroid for these activities, now the Cherng Department of Medical Engineering (MedE), was founded in 2013 as a bottom-up initiative conceived and organized by the faculty, 16 of whom are current affiliates. The main focus areas are in imaging and devices, specifically including biomaterials and bioimaging, medical nanoelectronics, chip-based diagnostics and medical devices. The mission strongly emphasizes translational impact, but

contributions to a broader base of scientific/engineering knowledge and to an enhanced graduate educational experience represent additional important goals. Notable programmatic milestones over the past five years include increasing the number of graduate students and postdoctoral fellows in the program (from 0 to 36 and from 3 to 17, respectively); hiring of one highly visible senior faculty in imaging and one highly recruited junior faculty in devices; securing a naming gift for the department; establishing a medical advisory council and a set of productive engagements with local hospitals; and launching an impressive number of medical startup companies based on licenses to Caltech technologies. Taken together, these accomplishments suggest a high level of enthusiasm and creative energy around this new initiative.

The Visiting Committee was highly impressed by the bold goals and by a rapid increase of momentum across the full breadth of research and the educational components of these programs. The Committee offers the following recommendations to ensure sustained vibrancy and growth.

- Continue to cultivate and build relationships with local medical communities by expanding the medical associates program. Explore means to enhance the Caltech presence at hospital facilities and medical schools, ideally through dedicated on-site laboratory and office space. Continuous, robust engagements with clinicians and healthcare providers, including nurses, are essential to a "top-down (i.e., application-based)" approach.
- Explore mechanisms to expand the FTE faculty, currently at 2.5, to a critical mass of at least five and perhaps as many as eight to ten. One possibility might be to engage with the new Chen Institute for Neuroscience, where novel neurotechnologies and imaging modalities could serve as common areas of interest. Others could include joint or research faculty appointments through partnerships with local medical schools.
- Identify means to increase the number of medicine-related courses available to graduate and undergraduate students, perhaps by hiring instructors to teach anatomy, biomechanics, surgical techniques and other essential topics, or by creating enrollment opportunities in courses offered at medical schools at USC, UCLA or other local universities.

3*: *The quality and effectiveness of the educational program and interactions between faculty and students (both undergraduates and graduates) are critical to Caltech's success. How can the EAS teaching program be improved? Are our mentoring activities sufficiently substantial and effective?

Caltech attracts some of the most capable students from the U.S. and around the world to its undergraduate and graduate programs, as well as many of the top early-career researchers to its post-doctoral appointments. As advanced technology has become ever more essential in industry and academia, student demand for EAS's programs has continued to rise, with about 10% increases in both undergraduate and graduate enrollment in the Division since 2014. To maintain its traditional standards of excellence in education and research, however, the EAS Division faces several challenges in undergraduate teaching and advising and in graduate student and post-doctoral mentoring.

The Committee strongly believes that the Institute has an obligation to its undergraduate students to strive to provide each of them with the distinctive "Caltech experience" which includes frequent faculty interaction and research participation. However, it is difficult to reconcile the Institute's widely advertised 3:1 undergraduate-to-faculty ratio (or 2.3:1 excluding freshmen) and all that

implies, with today's reality that, in three of Caltech's four most popular majors (CMS, EE and MCE) the actual ratio is about 9.5:1 (again excluding freshmen), and even higher for CMS majors. (See Table 2 below).

Accordingly, we recommend that EAS, with the full support of Institute leadership, move expeditiously to hire top-notch faculty for open CMS as well as EE and ME positions. We also urge the Division, with incremental funding from the Institute, to significantly increase the numbers of long-term instructors in computer science, while also materially enhancing their academic status (e.g., with "Professor of Instruction", "Distinguished Lecturer" or similar titles), campus privileges and financial compensation.

Table 2. Undergraduate Student/Faculty Ratios*

Caltech (Overall)	2.3:1
EAS Division	5.5:1
CMS, EE and MCE Departments	9.5:1
CMS Department	14.2:1

*Student Figures Reflect Undergraduate Declared Majors By Sophomores, Juniors, and Seniors in 2018

At the graduate student and post-doc scholar levels, career mentoring is also a significant problem that requires Division attention. Due in large part to the high teaching workload for CMS courses, faculty are frequently unable to provide the necessary research mentoring and career guidance that are so valuable to graduate students and post-docs (as well as upper-class undergraduates).

The CMS department has recently hired an "outreach director" who has made an enormous difference in the ability of students in CMS to find internship opportunities and links to job options after graduation. Undergraduate students in CMS seem to be uniformly enthusiastic about the mentorship this position provides and the doors it has opened. We commend the department for this initiative but believe additional emphasis on graduate student and even post-doc advising is needed. We also suggest that an outreach director, modeled after the CMS position, be considered at the EAS level to address this urgent need for all its students.

4*: *Increasing diversity in the student, post-doc and faculty populations is a significant goal at Caltech. Is the Division making observable progress in diversifying these populations? Are the climate of the Division and the efforts of the faculty appropriate in this regard?

As reported by the previous visiting committee, EAS made substantial progress in enhancing diversity at all levels in the five or six years preceding its 2014 review, bringing the Division to rough parity with other top engineering schools. Since then, progress has continued among some populations (e.g., undergraduate students and Division leadership) but largely stalled in others (e.g., graduate students, post-docs and faculty). (See Table 3 below).

The Committee notes that EAS's recent efforts to increase faculty diversity have been quite productive in terms of initial recruitment, with 12 of 27 (or 45%) of faculty offers to women and

URM and six of 13 (or 46%) acceptances in the same demographics in the last five years. Unfortunately, the Division has not achieved the same success with long-term retention. In addition to regular retirements, four women and URM faculty have left for other institutions in the last five years. Since there are often a complex set of reasons for why faculty members decide to depart, it is important to examine climate factors in the Division and its various departments to understand how satisfaction levels among faculty and students may affect retention. Therefore, the Committee recommends that a systematic climate survey be conducted, in part to determine if differences exist in the degree to which the importance of diversity has been internalized at the department level.

Table 3. Diversity Trends in EAS

Category	2018 Statistics*		2014-2018 Trend	Comments
Undergraduate Students	43%	14%	Up	Substantial Increases in CMS and EE Majors
Graduate Students	24%	5%	Flat	Somewhat Below Peer Averages
Post-Doc Scholars	18%	8%	Flat	
Division Faculty	17%	1%	Flat (Down for URM)	35% of New Faculty Since 2014 Are Women
Division Leadership	11%	11%	Up	

*First Figure Is % of Women, Second Figure Is % of Under-Represented Minorities (URM)

5*: *Roughly half the student body at Caltech is pursuing a degree in an EAS department, both at the graduate and undergraduate levels, but only one quarter of the Institute faculty comes from EAS. Can you suggest ways to manage this load given the constraints of budget, staff and other resources? With the increasing ratio of student/post docs to faculty, how can the Institute and the Division maintain the quality of advising and mentoring?

Compared to past decades, today's undergraduates are exhibiting substantially increased interest in courses and majors in EAS generally and computer science particularly. Indeed, as of 2018 58% of Caltech's undergraduates (411 of 713 sophomores, juniors and seniors) were EAS majors while most other undergraduates were taking EAS (usually computer science) courses. This student concentration is especially acute in the CMS department, which is the instructional home for about 35% of undergraduate majors and an additional 10% of minors but has only 6% of the Institute's faculty. (See Table 4 below).

The current popularity of computer science is reflected in larger class sizes and reduced faculty access for undergraduates, and has boosted the CMS sophomore, junior and senior undergraduate student-to-faculty ratio to nearly 14:1 vs. an Institute average of 2.3:1. Moreover, demand for computer science classes has also increased at the graduate level, such that combined CMS class enrollments have climbed by more than 20% in the past five years and 50% in the past 10 years. Based on national trends and industry demand, this situation shows no signs of abating in the foreseeable future.

Table 4. CMS Department Trends (2018 vs. 2014)

	2014	2018	% Change
Graduating Seniors (Major and Minor Degrees)	105	125	19%
Course Enrollments (Undergraduates)	2,250	2,560	14%
Course Enrollments (Undergrads and Grads)	2,850	3,445	21%
CMS Faculty (FTE)	17.5	18.0	3%

The CMS department has managed this situation remarkably well in view of the constraints it faced. The heavy teaching burden has been accommodated through employment of well-regarded lecturers and through somewhat larger classes. The department has hired an outreach coordinator, who helps students find internships and connect with employers, which is important since about two-thirds of CMS undergraduate majors go on to industrial jobs. Particularly effective has been the "hub-and-spoke" model of the "Caltech Computes" initiative, by which computation and AI expertise is embedded in many groups on campus. This is further enabled by the new AI4Science initiative, which pushes AI tools into other areas of engineering and science, for example through consulting and office hours by post-docs.

In spite of these efforts, some problems remain: (1.) CMS undergraduates have difficulty in finding research projects and those who are applying for graduate school have difficulty in getting recommendation letters from faculty; (2.) As noted above, students may not be receiving the full "Caltech experience" including close interaction with faculty; and (3.) The small size of the CMS faculty may be insufficient to maintain a premier computer science program, especially in the fast-moving fields of AI and machine learning, in which Caltech is missing some essential ingredients such as natural language processing expertise.

Therefore, while the Visiting Committee is impressed by the Division's response to date, we have several recommendations for additional actions:

- Caltech should hire at least five additional CMS faculties as soon as possible; this is a moderate and prudent response to the extraordinary increase in student interest in computer science, and it would not upset the intellectual balance of the Institute.
- Caltech also should hire additional high-quality, long-term lecturers in computer science, expanding what students view as the "bedrock" of the Institute's instructional capacity in this subject.
- Caltech should consider increasing the participation of undergraduates in "CS+X" initiatives so that they have greater access to research projects involving computer science across the Institute.

4. New Research Initiatives and Centers

The Committee was briefed on several relatively new research initiatives and one recently established center. We understand that these new research directions resulted from high-level strategic deliberations over the past three or four years, and most of them seem to have good

potential. However, due to the limited information and time available to the Committee to assess each initiative, we were not able to form a clear impression of Caltech's strengths and weaknesses relative to other academic and industrial research organizations that may be pursuing similar fields. Therefore, it was not possible for us to ascertain if Caltech is now, or likely can become, truly differentiated in all these areas. In addition, the Committee also wondered about whether the Institute is, or should be, pursuing major EAS-led research programs in several other high-impact areas that were not discussed, such as in geoengineering to offset the effects of climate change or nanotechnology applied in brain studies and other medical applications.

In the following particular research areas and the CAST laboratory, the Committee offers the observations and suggestions listed below for Division and Institute leadership.

Quantum Engineering. Caltech has a strong and admirable position in quantum science and engineering stemming from a sustained history of outstanding high-profile faculty research in physics, applied physics, materials science and chemistry. A principal objective of EAS's APhMS Quantum Engineering Center is to provide updated facilities that will continue to draw this community together, accelerating breakthroughs in collaborative interdisciplinary quantum research and innovation.

The QEC will seek to extend Caltech's leading work in quantum devices and optical physics into high-impact applications in metrology and information technologies, and support advances in quantum-engineered materials and associated first-principle models that target unprecedented proprieties for applications in extreme environments, medicine, propulsion, and energy.

The Visiting Committee recognizes that today's highly-favorable national funding climate in quantum information science may not be sustainable. Therefore, while the QEC will likely result in increased visibility and external funding opportunities, we agree that it should be instead predicated on enhancing synergies that will further nurture a differentiating area of strength for Caltech, while providing much-needed facilities upgrades to high-performing faculty and graduate programs.

As noted above (see page 6 above), the Committee supports the Division's plan to reconstruct the Watson Lab but believes a major donor's anchor commitment may be necessary to allow this project to move forward. We also offer the following suggestions for QEC development.

- APhMS should engage in in-depth discussions with faculty in PMA, CCE and BBE to ensure appropriate laboratory, classroom and office spaces are included in the new Watson design, to maximize the collaborative potential of the center.
- APhMS should also consider the best way to accommodate R&D testbeds for quantum-based systems, perhaps modeled after the approach used in the new Karman-hosted CAST laboratory (see page 13 below).

Sensing to Intelligence (S2I). The S2I initiative is responsive to widely-recognized opportunities for leveraging advances in AI with ubiquitous networked sensing/imaging technologies to improve our lives through transformative advances in areas including health, energy, and scientific discovery. In concert with CMS, EE envisions the S2I Center as drawing participation from disciplines including BBE, MedE, and MCE while leveraging applications expertise from enterprises such as CAST and JPL.

The S2I leadership team successfully articulated a number of research strengths in end-point sensor technologies. However, the Committee believes that the "holistic" design introduced by S2I should be more strongly emphasized in this effort, noting that many of the most impactful advances enabled by AI will be highly dependent on innovations in system engineering and integration. In addition, the Committee encourages S2I leadership to define real laboratory-based system-level demonstrators and testbeds that can provide collaborative teaching, research and innovation opportunities for end-to-end design and operations.

Resilient Cities. Recent natural disasters and other extreme events owing to Earth's ongoing climate change pose a timely and compelling case for new technological advances to foster resilient urban environments. The proposed research and educational program, led by the MCE department, envisions combining several existing centers and areas of research at Caltech, including material design and characterization, adaptive structures, climate modeling, earthquake laboratories, and geotechnics, into a "virtual center" for the study and mitigation of the impact of natural and man-made hazards in major metropolitan areas, such as the LA basin. A large-scale experimental laboratory, where resilient system models could be built and tested, would provide direct support to the center's activities.

The Committee believes there are great possibilities in this area, but encourages the Division to critically examine its current approach. With a view towards supporting its viability, we offer the following recommendations:

- Develop a process for effective integration of the various technical components of the center. Although many talented faculty members are expected to participate in the center, it is essential that a robust integration plan be in place at the outset to strengthen the prospects for success of this unique interdisciplinary center.
- Include a human factors element (currently missing in the proposal), since human error and faulty judgements have been the culprits in many catastrophic events.
- Couple this center into new initiatives at the federal level to address the country's aging infrastructure to enhance the potential for significant external support. Caltech should consider partnering with nearby universities (UCLA, USC, UC Irvine) some with experience in studying past disasters (Chernobyl, Katrina, Deepwater Horizon), to form a research hub in this area centered at Caltech.

Autonomous Systems. Established in 2017, the Center for Autonomous Systems and Technology (CAST) is a state-of-the-art inter-departmental (GALCIT, CMS, EE, MCE) and cross-divisional (EAS, GPS, JPL) center with 15 affiliated faculty members and eight JPL staff scientists. It is focused on advancing research and graduate education in autonomy and robotics, with applications ranging from space exploration and ground transportation to undersea operations and emergency response.

The Committee assesses the laboratory facilities that CAST has created as unique in academia, especially its indoor drone "wind wall" and its space robotics lab. CAST plans to expand its research capabilities in dynamics and control, machine learning and AI with the addition of five more faculty members by 2023-2024, which the Committee endorses, to allow it to realize its full potential in this growing area of advanced engineering. We note, however, that as presented to the

Committee, the plans for a capstone initiative involving relatively long-distance free-flight testing need to be carefully coordinated with all regulatory authorities, especially with the FAA.

5. Individual Department Summaries

Aerospace Engineering (GALCIT). A medium-size EAS department, GALCIT has 12 faculty members, offers M.S. and Ph.D. degrees, and possesses excellent (if somewhat underutilized) facilities. The largest near-term challenge for the department is funding for a few top-notch lecturers to cover course demand; the major longer-term challenge is the anticipated retirement of 50% or more of the faculty over the next 5-10 years. The Committee recommends that the department identify several highly promising junior faculty candidates that could be recruited to GALCIT over the next few years.

Applied Physics and Materials Science (APhMS). A relatively small department for undergraduates but the largest one for graduate students, APhMS has 12 faculty members with a fairly young average age. One of the biggest near-term challenges concerns the outmoded condition of the department's laboratories (see discussion of Watson Lab on page 6). In addition, as a relatively new combined department, APhMS would benefit from a more cohesive approach to education (especially for undergraduates) and stronger APh-to-MS internal collaboration.

Computing and Mathematical Sciences (CMS). See page 6 above.

Electrical Engineering (EE). Another medium-size department, EE has 11.5 FTE faculty and offers B.S., M.S. and Ph.D. degrees to approximately 12-14% of Caltech's undergraduate population and 8-10% of its graduate students. As is in case in CMS, the teaching workload in EE is quite high by Institute standards and the available budget for high-quality lecturers is limited. Along with the pursuit of a broad range of research projects, this has created considerable stress in the department and raises questions about its ability to compete for the best students and research funding. The Committee believes additional faculty members should be recruited soon, with a preference for early-career scholars, and additional funds should be provided for lecturers and teaching assistants.

Environmental Science and Engineering (ESE). Unlike the rest of EAS, ESE is a multi-division department with faculty from GPS and CCE as well as EAS. There is considerable concern about EAS's future involvement in ESE, given the small faculty size (3 from EAS), combined with expected near- and mid-term retirements and slow faculty recruitment decision-making involving multiple divisions.

Mechanical and Civil Engineering (MCE). In several ways, the MCE department is similar in size and composition to the EE department with 12 faculty, 10-12% of undergraduates and 8-10% of graduate students. Like both CMS and EE, MCE is experiencing increased student enrollments and would benefit from somewhat greater budgets to cover additional lecturers. The Committee commends the department for its five-year strategic plan for faculty hiring and research directions, which could serve as a model for other EAS departments.

Medical Engineering (MedE). See page 7 above.

6. Visiting Committee Process

This year's EAS Visiting Committee consisted of a good mix of academic and industrial leaders in relevant fields of engineering and applied science together with knowledgeable Caltech Trustees. All 13 members of the Committee were very active and engaged in our work during the campus visit and subsequent drafting and review of this report.

We appreciated the introductory and concluding sessions with the President, Provost and Division Chair, the preparatory material provided before the meeting, the well-organized agenda and effective faculty presentations, the engagements with students and post-docs, and the great administrative support for our work.

For future EAS reviews, the Institute might consider the following changes to the visiting committee process:

- Ask the department's external advisory committees to provide brief written summaries of what they view as the major challenges and decisions facing the Division and their departments.
- Adopt a somewhat standardized format and content for the white papers covering department status and research initiatives and centers. Also provide future committees with read-ahead copies of (or links to) the most recent annual report from the Office of Research Administration and any similar overview documents.
- Provide a more complete placement record for recent undergraduates in each EAS department.
- Add an extra half day to the visit schedule, such that the time on campus would consist of two full days and a final half day for wrap-up.

7. Conclusions: Top 10 Recommendations

The Committee appreciated the opportunity to review and discuss the EAS Division with many of its brilliant and dedicated faculty members, academic administrators, students and post-docs. Based on our interactions with them and the study of background materials provided by the Division, we offer the following compilation of our most important recommendations for Caltech leadership's consideration:

1. Develop a Division-wide integrated strategic plan ("EAS 2025") that includes approximate staffing levels and composition, competitive assessments of research initiatives, new infrastructure needs, and funding requirements and sources for the 2020-2025 period. Develop related department-level plans covering faculty hiring projections and research priorities.
2. Accelerate faculty hiring (with an emphasis on junior faculty) and increase lecturer and TA funding, most urgently in the CMS and EE departments.
3. Add introductory computer science courses to the core curriculum and introduce advanced discipline-specific CS courses in other divisions. Establish a systematic advisory program for freshmen and sophomores on the choice of majors and subsequent career opportunities.

4. Explore ways to enhance MedE's collaboration with local medical schools and hospitals, and to expand FTE faculty in concert with the new Chen Institute, with visiting scholar positions, and with joint or research faculty appointments with nearby medical schools.
5. Increase EAS-wide efforts to boost the fractions of U.S. graduate students and post-doc scholars, including by enhancing funding packages, housing options and diversity factors (see 6 and 7 below).
6. Carefully consider the pros and cons of fully-endowed funding for all graduate students from their first year through Ph.D. completion, as briefly addressed on page 5. This should be undertaken at an Institute level, not just at the EAS Division.
7. Conduct a comprehensive climate survey to determine if the value of faculty and student diversity is uniformly embraced throughout the Division.
8. Pursue the quantum engineering research initiative with all deliberate speed, while seeking a major donor for the Watson Lab reconstruction.
9. Consider the specific suggestions in this report for enhancing the other new research programs, such as an increased emphasis on systems integration in S2I and more aggressive pursuit of a broader Institute-wide interdisciplinary AI4Science initiative.
10. Finally, once these recommendations and other potential actions have been discussed and decided by Institute and EAS leadership, provide the necessary one-time and ongoing funding to expeditiously carry them through to completion.