Surfing at the Speed of Light
Can a Grand Challenge of Engineering Answer Big Questions of Physics?

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of Electrical Engineering and Physics
Co-chair NAE Grand Challenges Advisory Committee

UVA Physics Department
October 17, 2015
NAE Grand Challenges for the 21st Century

- Make solar energy economical
- Provide energy from fusion
- Develop carbon sequestration methods

- Manage the nitrogen cycle
- Provide access to clean water
- Restore and improve urban infrastructure

- Advance health informatics
- Engineer better medicines
- Reverse-engineer the brain

- Prevent nuclear terror
- Secure cyberspace
- Enhance virtual reality

- Advance personalized learning
- Engineer the tools of scientific discovery
Looking Back to the 20th Century:

Welcome!
How many of the 20th century's greatest engineering achievements will you use today? A car? Computer? Telephone? Explore our list of the top 20 achievements and learn how engineering shaped a century and changed the world.

1. Electrification
2. Automobile
3. Airplane
4. Water Supply and Distribution
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers
9. Telephone
10. Air Conditioning and Refrigeration

11. Highways
12. Spacecraft
13. Internet
14. Imaging
15. Household Appliances
16. Health Technologies
17. Petroleum and Petrochemical Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies
20. High-performance Materials
Implications of the Grand Challenges

• Don’t fit within any one discipline, or even within engineering

• Describe engineering in human-facing terms:
  – Sustainability, Health, Security, Joy

• Powerful tool for “Changing the Conversation”
To prepare UG engineering students with the skillset and mindset to address GCs over the course of their careers

Five critical components

1. Project or research activity engaging a Grand Challenge
2. Interdisciplinary curriculum – behavior, business, policy
3. Entrepreneurship
4. Global dimension
5. Service learning

Simon GC Scholar Maggie Hoff working on potable water project in Peru

Courtesy Martha Absher
Solving Grand Challenges will require I-Shaped Engineers

- Solutions must be Feasible, Viable, Desirable
  - Feasible → Engineering fundamentals
  - Viable → Economics and business knowledge
  - Desirable → Context of culture and social policy

A couple of stories...
Project Example: Revenue-generating Public Toilets in Togo

Reinventing the pit latrine
Human waste digested to biogas, then used to heat sterilize effluent.
Project Example: Sustainable fishery in Kenya

Teaching wave mechanics to protect fragile shallow water reefs
Project Example: Pratt Pouch

- HIV+ Women who give birth at home
- 20-50% have HIV+ children [1]
- Majority transmitted during delivery [1]
- 3TC, NVP and/or AZT can prevent transmission
- Drugs expires quickly out of the bottle (<1mos)


Duke Pouch 12 mos NVP
Duke Pouch 12 mos AZT
Duke Pouch 12 mos 3TC

Clinical Trials
Ecuador
Zambia
Tanzania
Namibia

Courtesy: Bob Malkin
TEACHING FOR THE FUTURE FIRST IN A SERIES

MORE ENGINEERING STUDENTS GET REAL-WORLD EXPERIENCE

Schools try to debunk it as a ‘fickle for geeks’

Dan Vergano
USA TODAY
DURHAM, N.C.

Hover Dan. The Panama Canal. The new iPhone folks are comping out of boy.

In very massive and handsheld, engineers have changed the world. Now the time has come for the world to change engineers. One student at a time.

"I'm a bit of an idealist. I've always wanted to help people," says Duke University engineering student Kathryn Latham, '11. "I think if more students pursued jobs that made a difference, the world would be a better place."

Latham's idealism took her to Bolivia this summer, leading a team of Duke engineering students building a 235-foot-long steel pedestrian bridge by hand. "She notes, to link two impoverished villages long separated by a deep gorge.

Taking young engineers out of lecture halls to practice their profession represents the cutting edge in reshaping the discipline, say educators and the field's leaders. Change is needed to face coming challenges in delivering energy, food, and clean air and water to the world's 7 billion people expected to live by mid-century.

"We have done a miserable job, by and large, of explaining just how engineering is essential and can change the world," says National Academy of Engineering President Charles Vest. In a nutshell, he says, that helps explain why only 4.5% of U.S. college graduates are engineers, while about 12% are in Europe and 21% are in Asia.

"This is an idealistic generation, despite everything going on in the economy, and they want to help people," Vest says. "We have to get them out of the lecture hall and show them how engineers do just that."

On Oct. 1, the academy will host a Grand Forum event in Washington aimed at showing how the discipline can fix the problem. It will feature educators, industry leaders and

Thomas Katsoulas sees success in the Grand Challenge program.

IMPROVING THE PIPELINE

A leaky "pipeline" dops engineering schools, where only about half of all incoming freshmen engineers graduate as engineers.

U.S. undergraduate engineers starting out as engineers and percentage graduating as engineers (2005 to 2009):

<table>
<thead>
<tr>
<th></th>
<th>Women</th>
<th>Men</th>
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<tbody>
<tr>
<td></td>
<td>2.6%</td>
<td>1.37%</td>
</tr>
<tr>
<td>Freshman</td>
<td>8.37%</td>
<td>15.6%</td>
</tr>
<tr>
<td>Seniors</td>
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Source: National Academy of Engineering, National Science Foundation, National Center for Education Statistics

"America produces just as many great kids as ever. They just don't see engineering as attractive all too often. Instead it's a 'can't-do' field for geeks," says President Richard Miller of Olney College in Needham, Mass., whose school was chartered in 1997 to reinvent how engineering is taught. "We need people who think differently, people who are creative, people who make things, people who can work in teams, not just alone on a computer."

Most radical at Olin, but increasingly at schools across the country, engineering students build things earlier in their college careers. They leave the heavy-hitting labs of large lecture courses for decades have defined their education with the messy business of building things that do, or don't, work.

At Olin, students have to build something in weeks-long projects as freshmen and start a business that sells to real customers before they graduate. "Our model is a music school with engineering as a performance art, and the studio time that students spend with each other is an environment part of their education," Miller says.

At Duke, Latham is a "Grand Challenge" scholar in a national engineering academic program.

"Khan Academy" online teacher Sal Khan, whose organization's short YouTube lectures on everything from calculus to civics have garnered more than 175 million viewers.

Since 2006, when a National Academy of Sciences report, "Rising Above the Gathering Storm," warned of eroding U.S. leadership in science and technology, alarm bells have rung over the brightest students skipping engineering for finance, medicine or other fields in an era of declining U.S. manufacturing.

Much of the problem comes in the university "pipeline" that carries kids from freshman chemistry to graduation, Vest and others say. Just 34% of women and 38% of men who started out as engineering majors in 2006 finished four years later.

Engineering professors in the past tried to wash out students in sink-or-swim programs filled with calculus problems, lectures and little else, but that culture has changed and is changing, Duke Engineering Dean Thomas Katsoulas says.

"It's a funny paradox. We want to make it as easy as possible to master the material, but we don't want to lower the level of mastery," he says.

Instead of a person solely skilled in filling graph-paper pages with neatly answered math problems the goal is a student grounded in teamwork and entrepreneurship as well. "We cannot solve all of our problems by technology alone," Katsoulas says. "They will require a deep understanding of human behavior."
Announcing a Special Workshop

EDUCATING ENGINEERS TO MEET THE GRAND CHALLENGES

APRIL 30-MAY 1, 2014
National Academy of Engineering
in Washington, D.C.

Leaders of engineering service-learning organizations, associations, industry and academia will gather in the nation's capitol next spring for a workshop focused on how the U.S. can best prepare future engineers to meet the NAE Grand Challenges for Engineering.

The goal of the workshop is to develop a consortium of 50 universities and organizations committed to incenting students to integrate specific curricular and co-curricular experiences that prepare them to address the Grand Challenges over the course of their careers. Attendance by invitation only.

Learn more at nae.edu/grandchallengesworkshop
"We the undersigned deans commit to educate a new generation of engineers expressly equipped to meet [grand] societal challenges...

“We affirm the importance of such aims as a reflection of our core values, as a source of inspiration for drawing a generation to the call of improving the human condition, as a driver for our nation and world economies, and as essential to US and global security, sustainability, health, and joy of living....

“Over the course of the next decade, we commit to graduating from each of our institutions 20 students a year who are prepared with this unique combination of skills, motivation and leadership to address the Grand Challenges....

Signed by 122 deans across the country
White House receives commitment letter
March 23, 2015
The End Game: Not just education but solutions to Grand Challenges

• Some expected and some unexpected advances since 2007...
Provide Clean Water

Dean Kamen’s Slingshot and Stirling generator

>1,000 liters/day < .001 cent per liter

Less electricity than a hairdryer

AIC-Chile Plasma Water Sanitization System

Un tubo que mata los gérmenes del agua
El sistema promete revolucionar la obtención de agua potable en el mundo, sobre todo en áreas azotadas por enfermedades como la cólera. El aparato convierte agua contaminada en un líquido sin presencia de virus, bacterias e microorganismos.

Ingreso del agua
El agua se introduce en la cámara, donde se encuentra el plasma que actúa como un catalizador que desactiva las partículas dañinas.

Sanitización
Al interno de la cámara, el agua se somete a un proceso de desinfección por efecto del plasma. El plasma genera ionización que desactiva las partículas dañinas, lo que resulta en agua potable.

Muerte de microorganismos
El plasma elimina microorganismos de diferentes tipos, lo que resulta en agua potable.

Plasma
El plasma generado se disipa en el aire, lo que garantiza la eliminación de microorganismos.

Inglés:

AIC-Chile Plasma Water Sanitization System

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2010: *Watson* wins on *Jeopardy*

2013: IBM Watson as an AI Physician
2010: Make Solar Energy Economical

Algae?

May 20, 2010
First synthetic life form

- FUEL
- FOOD
- VACCINES

Algae: 10,000 gal/acre/year

250M Cars $\rightarrow$ $\sim$ 0.0048 of US landmass
Personalized Learning

2011: First MOOC reaches > 100,000

2013

With Duolingo you learn a language for free while helping to translate the web.

900,000 learners + Machine Learning → surpassing Rosetta Stone
Engr Tools of Scientific Discovery

Laser and beam-driven plasma wakefields can miniaturize a large particle accelerator:

- **RF structure accelerator**  
  \( \lambda \sim 30\text{cm} \)

- **Plasma wakefield**  
  \( \lambda \sim 100\mu\text{m} \)

0-42 GeV in 3km  
42-85 Gev in 1m

Blumenfeld et al, Nature ‘07
Grand Challenge: Tools of Scientific Discovery

Accelerators!

Thinking big: Accelerators like the future LHC require long tunnels and powerful bending magnets.
Particle Accelerators: compact to country size

**Big Physics Questions and Applications**

### Large
- Verified Standard Model of elementary particles
- W, Z bosons
- Quarks, gluons and quark-gluon plasmas
- Asymmetry of matter and anti-matter
- Higgs Boson (cause of mass)
- Dark matter and energy?
- Faster than light particles?
- Origin of hi-energy cosmic rays?
- Beyond the Standard Model?

### Compact
- Medicine
  - Cancer therapy, imaging
- Industry and Gov’t
  - Killing anthrax
  - Lithography
- Light Sources (synchrotrons)
  - Bio imaging
  - Condensed matter science
Astrophysical Jets -- the ultimate beam-plasma interaction laboratory

Radio Jets from Galaxy 3C296

X-rays from Crab Nebula Pulsar
Particle Accelerators

Requirements for High Energy Physics

• High **Energy**

• High Luminosity (event rate)
  • \( L = \frac{fN^2}{4\pi\sigma_x\sigma_y} \)

• High **Beam Quality**
  • Energy spread \( \frac{\delta\gamma}{\gamma} \sim 0.1 - 10\% \)
  • Low emittance: \( \varepsilon_n \sim \gamma\sigma_y\theta_y < 1 \text{ mm-mrad} \)

• **Low Cost** (one-tenth of $10B/TeV)
  • Gradients > 100 MeV/m
  • Efficiency > few %
<table>
<thead>
<tr>
<th>Conventional Accelerators</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Limited by peak power and breakdown</td>
<td>• No breakdown limit</td>
</tr>
<tr>
<td>• 20-100 MeV/m</td>
<td>• 10-100 GeV/m</td>
</tr>
<tr>
<td>• ILC = 20km /0.8 TeV</td>
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</tbody>
</table>

**Particle Accelerators**

*Why Plasmas?*
Simple Wave Amplitude Estimate

\[ \nabla \cdot E \sim ik_p E = -4\pi en_1 \]

Gauss’ Law

\[ k_p = \frac{\omega_p}{V_{ph}} \approx \frac{\omega_p}{c} \]

\[ n_1 \sim n_o \]

\[ eE \sim 4\pi en_o e^2 c / \omega_p = mc \omega_p \]

or

\[ eE \sim \sqrt{\frac{n_o}{10^{16} \text{ } cm^{-3}}} \times 10 \text{GeV/m} \]
Concepts For Plasma Based Accelerators*

- Laser Wake Field Accelerator
  A single short-pulse of photons

- Plasma Wake Field Accelerator (PWFA)
  A high energy electron bunch

- Drive beam
- Trailing beam

- Wake: phase velocity = driver velocity
  \((V_{gr} \text{ or } V_b)\)

*Proposed by John Dawson
Dream beam
The dawn of compact particle accelerators

Electrons hang ten on laser wake

Huge particle accelerators have been so far required to perform the kind of research that turns on high-energy collisions of subatomic particles, the fundamental building blocks and forces of nature. Now, however, a new technique, the laser-plasma wakefield accelerator (LPWA), promises to revolutionize the field of particle physics—and even make high-quality beams available in the near future. This technique, which has been demonstrated in the past few years, involves the generation of intense laser pulses that interact with a plasma target to create a plasma wakefield, which can then be used to accelerate particles to high energies. The LPWA is a very promising technology that could revolutionize the field of particle physics, as it offers the potential to provide high-quality beams of particles for use in various applications, such as medical research and materials science.
Parameters: \( n_e = 6 \times 10^{18} \text{ cm}^{-3} \), \( a_0 = 1.3 \), \( t = 30 \text{ fs} \)

Results obtained with 1m off-axis parabola:

\( w_0 = 18 \mu \text{m} \), \( z_R = 1.25 \text{ mm} \)

J. Faure et al., Nature 2004
Recipe for a Monoenergetic Beam

a. Excitation of wake (self-modulation of laser)
   Onset of self-trapping (wavebreaking)

b. Termination of trapping (beam loading)
   Acceleration

c. Dephasing
   If $L > \text{or} < \text{dephasing length}$: large energy spread
   If $L \sim \text{dephasing length}$: monoenergetic

T. Katsouleas, Nature 2004
Experiments are at threshold of a scalable robust regime

• Similar sequence of events:
  
  – The front of the laser pulse loses energy (*local pump depletion*) and etches back.
  
  – Wake grows and electrons are self-injected at the tail of the ion channel
  
  – High quality beam load forms $\varepsilon_N \sim r \theta \sim 1 \mu \times 1 \text{ rad}=1 \text{ mm-mrad}$

(100’s of pCoul from a “cathode” spot of $1 \mu$)

W. Lu, M. Tzoufras et al., UCLA
Scaling laws for monoenergetic regime

Verification of the scaling through simulations

If the laser can be guided (either by itself or using a plasma density channel), one can increase laser power and decrease plasma density to achieve a linear scaling on power:

$$\Delta E \propto P$$

W. Lu et al., UCLA
US and Worldwide Experimental Effort on Plasma Accel

Laser Wake Expts
Electron Wake Expts
e-/e+ Wake Expts
Review of Experiments

Beam drivers

The E-162/E-164 Collaboration:


Stanford Linear Accelerator Center


University of California, Los Angeles

T. Katsouleas, S. Deng, S. Lee, P. Muggli, E. Oz

University of Southern California
PWFA Experiments @ SLAC
Share common apparatus

Located in the FFTB

Ionizing Laser Pulse (193 nm)
Li Plasma $n_e \approx 6 \times 10^{15}$ cm$^{-3}$

$E = 30 \text{ GeV}$

Optical Transition Radiators

Spectrometer

Cerenkov Radiator

25 m

Not to scale!
E164X breaks GeV barrier

$L \approx 10 \text{ cm}, n_e \approx 2.55 \times 10^{17} \text{ cm}^{-3}, N_b \approx 1.8 \times 10^{10}$

Energy gain exceeds $\approx 3 \text{ GeV}$ in 10 cm

M. Hogan, et al. (PRL, July 2005)
Data is very reproducible!
Data is very reproducible!
Doubling energy in a plasma wake

ASTRONOMY
The Milky Way's particle accelerator p10

LHC FOCUS
Processors size up for the future p18

COSMIC RAYS
RF antennas provide a new approach p33

Work supported by DOE
X-Ray emission from Betatron motion

I \sim 10^{19} \text{ photons/s}.1\% \text{bw-mm}^2\cdot\text{mr}^2 @6 \text{ keV}
II. Wakes and beam loading are similar but…

• Lasers can more easily reach the peak power requirements to access large amplitude plasma wakes
  - $100k for a T3 laser vs $5M for even a 50 MeV beam facility

• Lasers can be bent more easily

• Average power cost for beam vs. laser technology sets timescale for HEP app
  - $10^4$/Watt for lasers currently x 200 MW ~ $20T$, but there is much current research on developing high average power lasers.
  - $10$/Watt for CLIC-type RF x 100 MW
3-D simulation of particle beam refracting as it exits plasma (blue)
Electron Beam Refraction At Plasma–Gas Boundary

Symmetric Channel Beam Focusing

Asymmetric Channel Beam Steering

θ ∝ 1/sin(φ)

θ ≈ φ

r_c = α(n_b/n_e)^{1/2} r_b

• Vary plasma – e^- beam angle φ using UV pellicle

• Beam centroid displacement @ BPM6130, 3.8 m from the plasma center

P. Muggli et al., Nature 411, 2001
High power beams tend to blow holes

- 30 GeV e-beam penetrates several mm’s of copper...

But we have seen...

- 30 GeV beam incident on 1mm of dilute gas (one million times less dense than air) refracts and even...bounces off (total internal reflection)!

Courtesy T. Raubenheimer, M. Ross
Plasma Acceleration has put Physics at the Forefront of Science

Acceleration, Radiation Sources, Refraction, Medical Applications

From good Physics to a good Collider is a Grand Challenge worth pursuing.
Evidence for a Brightness Transformer (or 2nd beam generator) in the SLAC PWFA Experiment (E-167)

Plasma Source: neutral Li vapor confined by He

Trapped bunch

drive beam

trapped beam
Unique Source of Bright and Short e- Beams

Osiris Simulation

<table>
<thead>
<tr>
<th></th>
<th>Trapped Bunch</th>
<th>SLAC Beam Driver</th>
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</thead>
<tbody>
<tr>
<td>$I_{\text{peak}}$ (kA)</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>FWHM ($\mu$)</td>
<td>2 (6 fs!)</td>
<td>65</td>
</tr>
<tr>
<td>Emittance (mm-mrad)</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>$B_n$ (A/m$^2$-mm$^2$)</td>
<td>$1.5 \times 10^{15}$</td>
<td>$7 \times 10^{12}$</td>
</tr>
</tbody>
</table>

Peak at 11 GeV

FWHM ~4%
Laser acceleration of ions from solid targets

Laser:
- few J / ~1 ps (>10 TW)
- $I\lambda^2 > 10^{18}$ W cm$^{-2}$ µm$^2$

Incident laser

Bulk Target (Al)

I. ambipolar expansion


II. sweeping acceleration


III. sheath field acceleration


if target is heated $\Rightarrow$ efficient acceleration of heavy ions

**Accelerator Summary**

On ultra-fast timescales, relativistic plasmas can be robust, stable and disposable accelerating structures

No known show stoppers to a plasma collider, but not enough known to answer the question

The race to the energy frontier is revealing rich physics and applications along the way

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*Plasma*

$\lambda = 100 \mu m$