

# American Physical Society New England Section Newsletter

## Editors

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Franz J. Rueckert

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Spring 2019

## Spring 2019 APS/AAPT-NES Joint Meeting March 22-23 **Springfield College**

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### Theme: How Physics Research and Physics Teaching Can Inform One Another

In the last 25 years, research into Physics education has grown exponentially. At the same time, Physics faculty have continued to push the limits of experimental and theoretical investigation. No matter the sub-field or specialization, at their core, all Physics faculty are teachers. The symbiotic relationship between teaching and research, and especially how the two can inform one another, is an area of great interest and has resulted in many fruitful collaborations.

All members of APS are invited to submit abstracts for presentations or posters for future APS-NES meetings. Undergraduates are strongly encouraged to apply. If you are not a member, you are welcome to join APS. Presentations and posters do not need to match the theme of the invited speakers or the theme of the given meeting.

#### Invited Speakers:

Dr. Bethany Johns, American Institute of Physics  
Dr. Andrew Duffy, University of New Hampshire  
Dr. Natasha Grace Holmes, Cornell University

#### Local organizing committee:

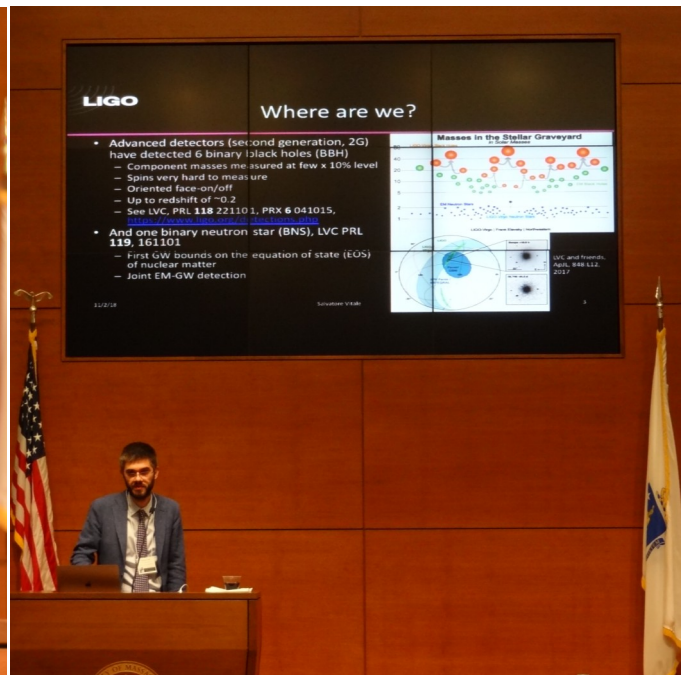
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## Photo Recap: Fall 2018 APS-NES meeting at **UMASS Dartmouth**

**University of  
Massachusetts  
Dartmouth**

**Theme:  
Gravitational  
Wave  
Astronomy &  
Computational  
Physics**

**November 2-3  
2018**



**Keynote Speaker Salvatore Vitale MIT**

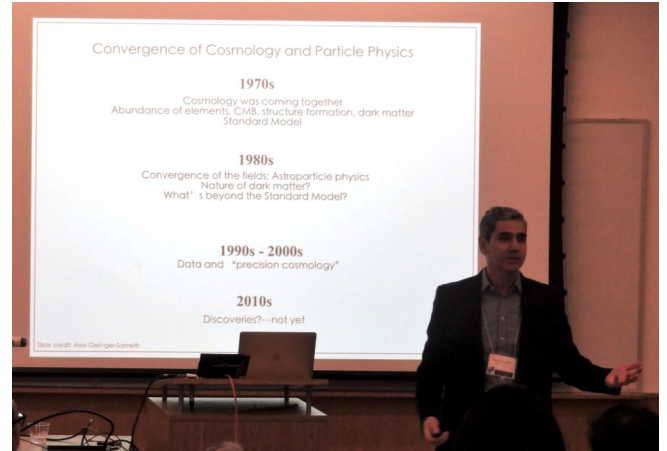
**The Scientific Potential of Third-Generation Gravitational-Wave Detectors**



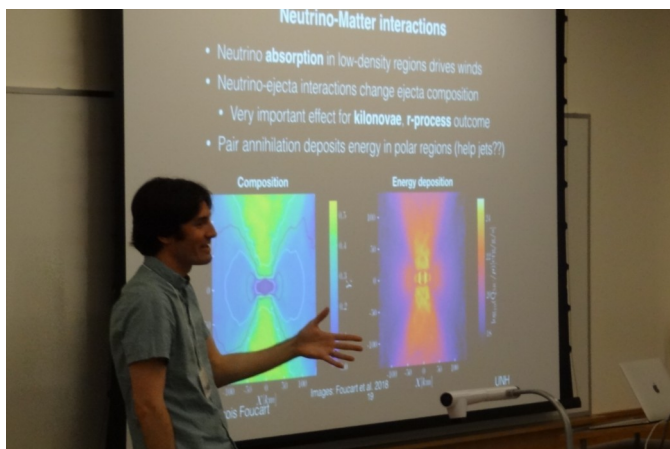
## Recap of the Fall 2018 APS-NES: Invited Speakers



Robert Coyne takes questions about astronomical observations using gravitational wave detectors.



Savvas Koushiappas relates a history of cosmology and particle physics



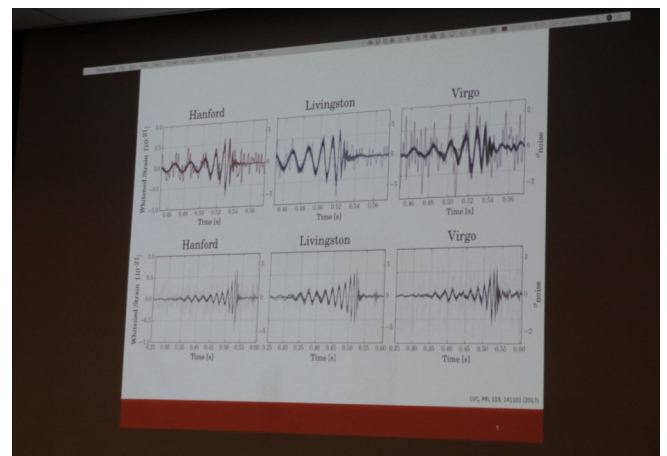
Francois Foucart explains neutrino-matter interactions in merging black holes



Carl-Johan Haster gives more detail regarding the gravitational wave data from compact binaries.

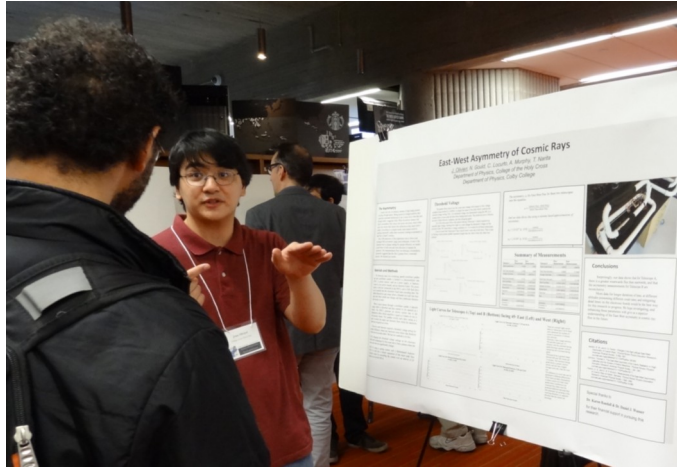


A captive audience follows every detail.



Carl-Johan Haster presents notable detection data.

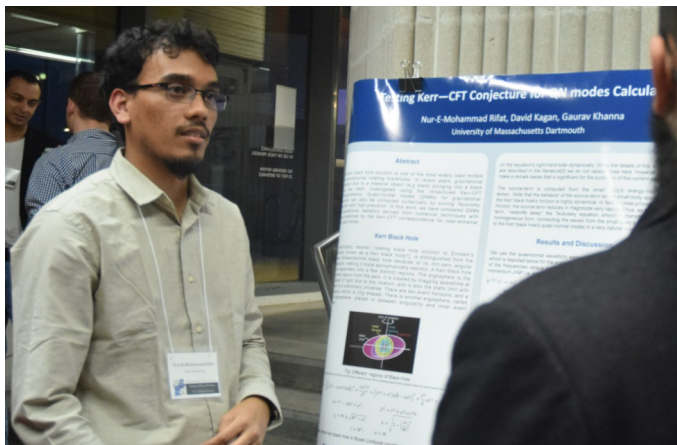
## Recap of the Fall 2018 APS-NES: Poster Session



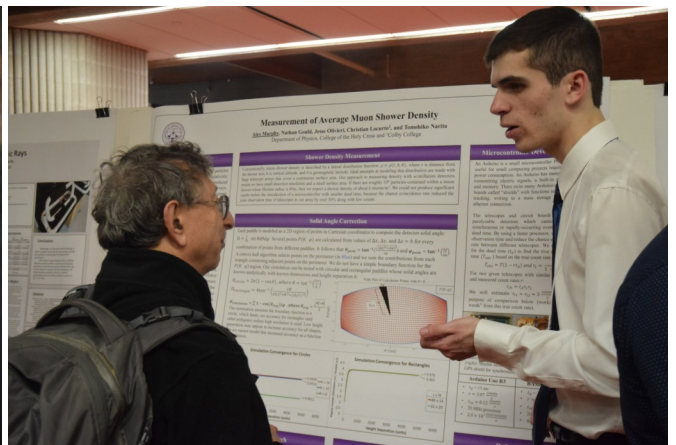
Jesse Olivieri presents his poster titled "East West Asymmetry of Cosmic Rays"



Chantal Umhoza explains coated laser diodes in external cavity diode laser systems



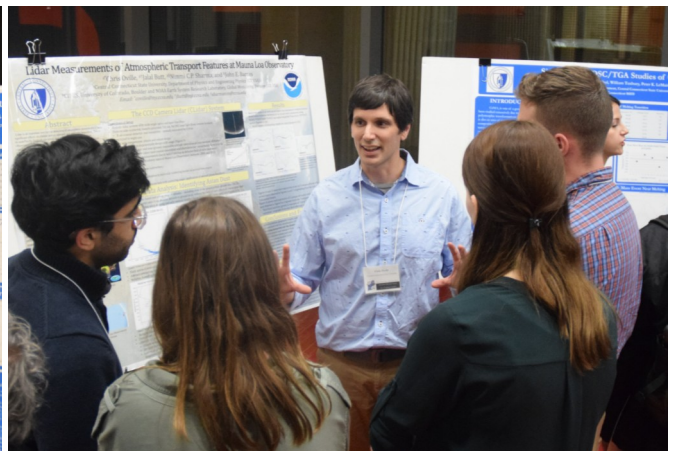
Nur-E-Mohammad Rifat details testing the Kerr-CFT conjecture for QN modes calculation



Alex Murphy of the College of the Holy Cross describes measurements of muon shower density



Caroline Mallery and Alicja Urbanczyk discuss her work on simultaneous DSC/TGA studies of  $\text{CsNO}_3$



Chris Oville of Central Connecticut State University leads a group discussion



## Recap of the Fall 2018 APS-NES: **Banquet**



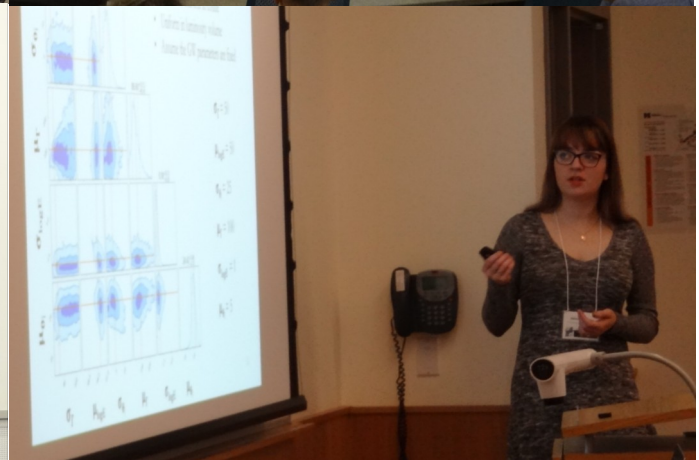
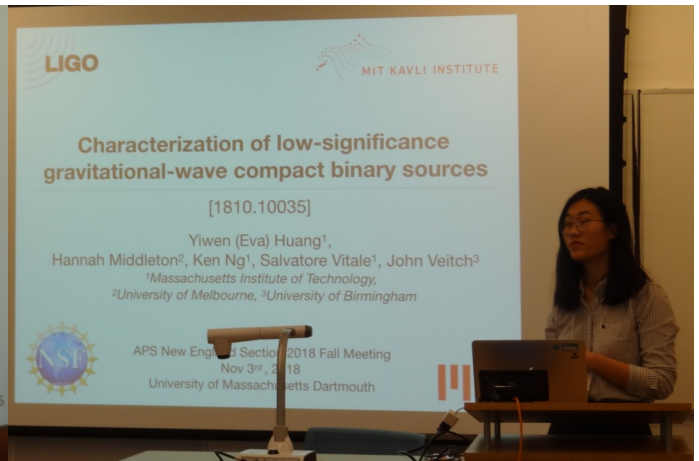
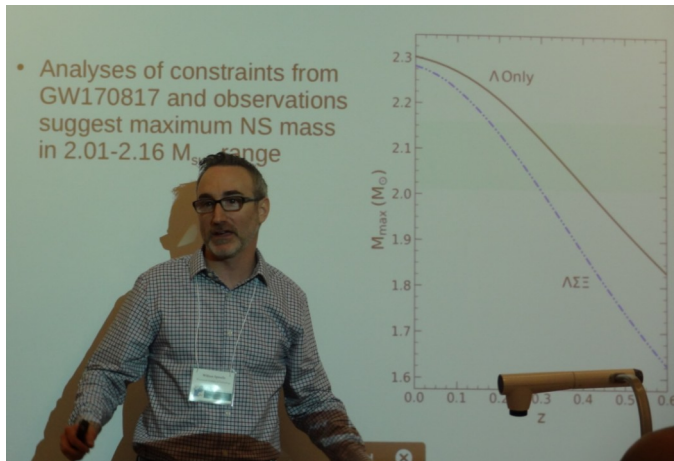
Do you have interesting Physics related articles, new programs, research reports, physics talking points, opinion articles, or responses to opinion articles that you will like to share with the New England Physics Community?

Send them to

James G. O'Brien ([jobrien7@springfield.edu](mailto:jobrien7@springfield.edu)) and Franz J. Rueckert ([rueckertf@wit.edu](mailto:rueckertf@wit.edu))



## Recap of the Fall 2018 APS-NES: Contributed Sessions



### Contributed Speakers

William Spinella  
Dwyer Deighan  
Feroz Shaik

### Contributed Speakers

Yiwen Huang  
Gabriel Casabona  
Sylvia Biscoveanu



## Spotlight on the Host Institution: **Springfield College**



**The James Naismith (the inventor of basketball) Green is the center quad on the Springfield College campus.**

### **Springfield College: Spirit, Mind and Body**

Springfield College is a private, coeducational institution founded in 1885, and which inspires students through the guiding principles of its *Humanics* philosophy—educating the whole person in spirit, mind, and body for leadership in service to others. That philosophy transcends across the main campus in the heart of western Massachusetts and its regional campuses across the country where the College educates nearly 5,000 students. At Springfield College, great emphasis is placed on helping students grow their whole person, enter fields that help others, and serve as leaders in their communities, organizations, and companies, at home and around the world.

Springfield College offers bachelor's, master's, and doctoral degrees, and serves as a destination for those seeking a well-rounded education, strong academics, experiential learning opportunities, and active and fulfilling co-curricular and athletic involvement. Our majors blend traditional coursework with experiential learning such as internships, fieldwork, student teaching, and practicum. The blend of classroom and real-world experience is what provides our students with skills, knowledge, insight, and networks to achieve their career goals upon graduation. The College master's and doctoral programs introduce students first-hand to community action projects and clinical, research, and practical placements. For more than 35 years, the School of Professional and Continuing Studies has been serving adult learners at the main campus and at the six

regional campuses across the country, including offering face-to-face and fully online courses.

Annually, students, faculty, and staff volunteer for more than 120,000 hours of community and other service opportunities, efforts rooted in the *Humanics* philosophy. The traditional New England main campus sits on the shores of Lake Massasoit, giving the feel of an oasis in the middle of the third largest city in Massachusetts. Expedia.com named Springfield College one of the 15 most beautiful college campuses.

The College has a strong alumni base with more than 45,000 strong, providing leadership and making a difference—as coaches, corporate CEOs, social workers, authors, medical professionals, athletic trainers, software engineers, and more, in 60 countries worldwide.

Within all that history and academic excellence resides the Springfield College Department of Mathematics, Physics and Computer Science. This multi-disciplinary department adapts the *Humanics* philosophy in many new and creative ways. In the following, a few highlights of the departments' activities are provided. Springfield College, and the Department of Mathematics, Physics and Computer Science is pleased to host physics professors, researchers, educators and colleagues at the Joint APS/AAPT New England Section Meeting. We hope you enjoy your time on our beautiful campus.

Authors: Judith Kelliher and James G. O'Brien



**The Newly renovated H.C. Smith Learning Commons is the center for academic life on the campus.**

## Spotlight on the Host Institution: Springfield College continued



*The Department of Mathematics, Physics and Computer Science takes PRIDE in Springfield College Traditions.*

### The Department of Math, Physics and Comp. Sci.

As a Multi-Disciplinary department, Mathematics, Physics and Computer Science (MPCS) faculty have been active in trying to create new and exciting courses and programs that would be appealing to the Springfield College student. The cornerstone of the college, the *Humanics* philosophy stresses the importance of the movement of the body. To this end, the faculty offers a unique, required course, for our students majoring in athletic training, exercise science, and physical education: *The Physics for Movement Science*: a course studying physics, using physical activities that involved the human body in motion.

With modern video technology and video software being readily accessible and affordable, basic motion analysis of the moving body could be infused into the course. Several years later, Professor Zenobia Lojewska extensively studied the literature to find out how other instructors are modifying their introductory physics courses taught to life sciences. She noticed that the human body was often used as a theme to introduce topics in classical mechanics. Coupled with the biomechanical expertise of Professor Jeff Gagnon, the two began a collaboration which yielded movement science laboratory exercises for a wide range of topics. The course now boasts engaging labs such as *Bicep Force During an Isometric Contraction*, *Impulse Momentum to predict the Max Height of a Human Jump*, *Design of a Baseball Bat for Maximum Trajectory* and *Modeling the Swinging Leg During Gait as a Pendulum*. To further bring the concepts to life in the lecture, students must present final projects on how topics studied in the course can be applied to analyze human motion or sports. The reception to presenting the wonders of physics through movement science has been very positive at Springfield College. Based on this

success, Jeff and Zenobia have been motivated to share their experiences with others who may also be interested in introducing human movement activities to engage their students. They have spoken about their work at numerous conference presentations and are featured in a workshop at this year's joint NES-AAPT/APS conference at Springfield College.

Springfield College has a strong tradition rooted in athletics. Several years ago, Professor Andrew Perry launched the now popular minor in Sports Analytics. Sports analytics is a rapidly growing field which can be defined as the analysis and interpretation of sports statistics, and which caught the eye of the general public with the 2011 film *Moneyball*. The department currently hosts 35 minors, many of whom major in Sports Management or Sports Journalism. The program features foundational courses applicable to Sports Analytics such as mathematics, combinatorics, statistics, databases and more. The minor concludes with a capstone seminar course where students undertake advanced analyses of current sports using all available information up to and including play-by-play data. Many students have completed the minor and have presented their capstone projects in poster sessions regionally and nationally. Past projects have included topics such as “*quantitative evaluations of the total contributions of particular players toward winning*” and “*defensible probabilistic predictions of future sporting events*”.

The future of the MPCS department is strong. In the last year alone, Springfield College and the department have been the host of prestigious events such as SCUDEM, NERDS and now the joint meeting of the New England Sections of APS and AAPT. The department is optimistic that more events such as these will welcome scholars from many disciplines from the surrounding areas to our beautiful campus.

Authors: Z. Lojewska, J. Gagnon, A. Perry and James G. O'Brien





## Opinion: The Future of Early Careers in Physics

I want to start with a full disclosure. Or perhaps a partial disclosure; "full" may provoke the dismissive TLDNR. Disclosure item: I hope to provoke engagement (perhaps disagreement). I might slightly (perhaps not slightly) overstate things. Disclosure item: Although I am the past and future Chair of the APS New England Section, I am an employee of the AAPT. (I hope that you feel I can be trusted despite this.) Some of the remarks I make here were previously made in a talk at a meeting of the AAPT New England section.

I would like to whine a bit on behalf of those who are early in their careers in physics. Although APS has members from industry, its membership is overwhelmingly academic, and it is to them, and for them, that I will focus my whining. Whining, though a good beginning is not a good end, so they – and those who support them – will find some suggested remedies if they keep reading.

The first target will be state, and more generally local, funding. There were severe cutbacks in funding of higher education due to the crash of 2008. Although the economy has healed, state funding has not, and the great majority (2/3) of institutions of higher learning that are funded locally are crumbling ivory towers. Twelve states, in fact, have per pupil educational funding below that before the crash. New England states are not among the shamed 12, but let's not party. Perhaps the pendulum will swing back, but now the pendulum is far over to one side, and its pivot is rusty.

One element of this pivot rust is understandable, but tragic (and here I may be using my prosaic license to overstate). State legislatures want accountability, and they should have accountability. Unfortunately, when it comes to accountability something must be counted. What do you count in education? Diplomas. This has created a situation in which publicly funded institutions compete for students. One way of being successful in this competition is to lower standards. In non-prestige schools, students have become the always-right customer and the long-term consequences of this race to bottom are obvious.

Is no one thinking this through?

The prestige institutions are not part of the need to sing a siren song to those looking for a college diploma. They can continue to pick and choose the small fraction of the large number of students who (with great justification) see a degree from Harvard, Stanford, MIT and their ilk as the key to the door of the good (or at least the wealthy) life.

A terrible consequence of this competition is to destroy, or at least seriously question the belief in education as the great leveler. The 2011 book "Academically Adrift" made an impressive argument that education in the non-prestige schools actually increased the gap between the haves and have nots. Tests of creative thinking showed some minority groups actually getting worse during their college years. And then there is the most important advantage of a generalized Ivy League education: the "social capital," the real who-you-know basis of the path to the good life in what falls well short of a meritocracy. College education results not in leveling, but in magnifying the tilt of the playing field of careers.

Is no one thinking this through?

Within institutions there is a smaller scale version of this competition. What can departments offer to draw in students? They can boast of lucrative future careers or an easy path to a diploma. Consider where this leaves physics departments. Bankable career? Easy courses? So does this mean the end of physics departments? The attempts to do this have not yet been successful, but how long can this go on? With an unsteadily dwindling number of majors, and more steadily dwindling research funds, is it only a matter of time? Can physics departments continue to take comfort and security in the fact that engineering students have to take introductory physics? After all, introductory physics acts as a gatekeeper course for engineer wannabes. There is no comfortable security there because engineers can teach those introductory courses, and this is what is done in many countries. The engineers can do their own gate-keeping; it will be a small price to pay for the extra professorial slots they will get.

What then does a young person face when facing a physics career in academics? The cutback in state/local support means a greater teaching load. It means greatly reduced support for staff, travel, publication, experimental equipment and the other necessities of academic life; in turn this means more demands on instructor time. Yet requirements of publication remain, although in many cases these requirements are relics of earlier times and are now little more than traditions at institutions in which research plays no real part of the education offered. Perhaps there is some excuse in that having a paper accepted for publication in a respected journal is a quantifiable accomplishment, while judging teaching has the same sharp objectivity as judging abstract art or ice dancing.

## Opinion: The Future of Early Careers in Physics (continued)

Is no one thinking this through?

And now, there is yet another unkind cut. For (one supposes) noble reasons, those who think that they know best have pushed for funding agencies to require that funded research be made open access, requiring no subscription. If there are no charges paid to a publisher for the right to read an article, there must be charges paid to publish the article, charges once called "page charges," which have now been euphemized to APCs (article processing charges). So in addition to having to find a way to do research, teach pretty much full time, struggle through without staff support, and make up makeup exams for always-right student customers, the early career physics instructor, must pay a thousand dollars to publish the article she needs to have published so that she will be allowed to continue in this chosen life.

Is no one thinking this through?

Let's start thinking it through. The APS is effective, or at least active, in slowing the rate of decrease of federal support of research. But this does not directly help those in the institutions that are not primarily research institutions. It does not help the vast majority of the 2/3 of the institutions that are publicly funded. That help requires local involvement, and the APS does not have the resources or structure to be active at the state level.

Who can pick up the baton when there hasn't even been a baton to drop? Should assistant professors follow the success of the teachers in West Virginia and Los Angeles? Should they strike and picket? No, I can't picture it either. What can be done is local advocacy, and I propose that the most appropriate groups to be saddled with this responsibility are the regional units of the APS and AAPT.

What could we do? I think that the first two commandments are: find friends, don't make enemies. The finding friends would include asking around who in the state legislature, county government etc. is interested in STEM education. One name leads to another, and another. Pretend you know what you're doing and pretty soon you will know what you are doing. Whatever you learn to do or to avoid should be shared with others who share your goals. Avoiding enemy-making starts with contacting the government relations people at your institution and telling them what you are doing, and learning what to avoid doing. The last thing you want, down there on your list even below picketing, is to ask for something from a foundation that your institution has been working on for a big

donation.

In the early stage of advocacy it will probably be best to listen and learn, but I suggest a few general principles to keep in mind, messages that can be tuned and delivered when and if necessary.

The first is common and expected: A technically educated workforce is what draws the kind of companies that local leaders want to attract.

The second message is a less common sermon: A technical education does not mean training technicians; that can best be done by the companies that need them. A true technical education requires the infrastructure of higher education, with a reasonably broad background of entangled courses. This means math, physics, chemistry, computer science and more. *Education* is an infrastructure -- training is not. The companies that are sought by localities seek an educated workforce.

The third message is distinct, though linked to educational infrastructure; it is the issue of cost efficiency. If STEM educational facilities are allowed to run down it will be unnecessarily expensive to build them back up. Luring good instructors to decayed institutions will require higher salaries than are typical of the market. Luring career-oriented students to institutions without good instructors will require special incentives. Good researchers are unlikely to come to research settings that are lacking the graduate assistants that researchers need; good graduate students will not go to institutions without the researchers who will start them on a career. As some states found by letting their public universities run down, this leads to the expenditure of a great deal of money and takes a great deal of time. State legislators: If you want to reduce inevitable costs, increase support of STEM education *now*.

I will end by plagiarizing Robert Park, the APS Director of Information from 1983 to 2006 and my role model as a curmudgeon: "Opinions are the author's and are not necessarily shared by the APS, but they should be."

Author: Richard Price

Note: The views shared here are the sole opinion of the author. These discussion pieces are meant to begin a dialog between APS-NES members. See page 11 for more details.



## New Opinion Articles

Gatherings such as the APS-NES regional meeting give scholars and teachers a chance to catch up, disseminate new work, and ultimately have a conversation with one another about the science of the world around us. However, the conversations should not end when the final presentations conclude. The time we spend together generates many hours of dialog, some of which should be shared with the greater community. Since the APS-NES newsletter is the written record of the meetings, members have expressed interest in the inclusion of an opinion and response segment. In this issue, the first opinion piece, titled "*The Future of Early Careers in Physics*" by Dr. Richard Price is featured. In future issues, it is the hope of the editors that this trend will continue and expand with future responses to the opinion pieces stated here.

Do you have an opinion? Do you have a response to the featured opinion in this article? If so, please send your written thoughts to:

James G. O'Brien, jobrien7@springfield.edu  
Franz J. Rueckert, rueckertf@wit.edu

Note: Opinions and responses may be lightly edited for clarity and brevity.

## Invitation from the Editors

To the Members of the APS-NES Community,

On behalf of the APS-NES Executive Committee, we wish to thank you for reading our newsletter. As you are aware, the APS-NES newsletter is a long standing tradition of our meetings. These letters allow us to reflect on past meeting experiences, learn about host institutions, and share some photographic memories. However, these letters are also a place to communicate the items of interest in our physics community. To this end, we ask that anyone interesting in contributing an article, story, opinion piece, opinion response, or physics experience to please reach out to the co-editors. In previous newsletters, topics of current physics, new pedagogy, obituaries, Nobel prize summaries, advancements in engineering, undergraduate research, and global events have all been discussed.

This newsletter thrives on participation from our dynamic group. It is our intent as editors to deliver the same experience as before while exploring some new features.

Co-editors:

James G. O'Brien and Franz J. Rueckert

## Undergraduate Spotlight!

For years, the APS-NES chapter has been a strong supporter of undergraduate research and its importance in today's physics education. Evidence of this can be seen in the strong attendance record at APS-NES meetings by undergraduate students, as well as the increasing number of poster and oral presentations by undergraduate student collaborations. For these students, a poster or talk presents new challenges that are not typically encountered in the classroom and provides practice for future careers in science. Typically, a first poster is a predecessor to a first paper, and in some instances represents the first exposure to a peer review process. To this end, the APS-NES newsletter will feature a spotlight on undergraduate research projects presented at APS-NES meetings. These highlight articles will be short and concise yet provide the writers a chance to tell a full story in a professionally written form. Light peer reviewed feedback will be provided and the best of these will be featured in upcoming issues of our newsletter. **Please help us in spreading the word to your undergraduate students.**

## APS welcomes AAPT

At the Springfield College meeting this Spring, the two largest physics organizations have come together for a joint New England Section meeting. A joint meeting has not happened since 2015 at Dartmouth. The leadership of APS-NES and AAPT-NES have worked collaboratively with the local organizing group of Springfield College faculty to deliver a meeting that both groups will find exciting and engaging. Many new items are featured in the spring meeting including:

**Friday Sky Observation Session:** Springfield Main Quad

**Saturday Workshops:**

*Learning Physics Through Gaming*

*Gravity Waves and Plancks' Constant*

*Teaching with Telescopes*

*Biomechanics: The Physics of Movement Science*

Join APS-NES  
at  
[www.aps.org](http://www.aps.org)

# The 2018 Nobel Prize in Physics

Douglas S. Goodman<sup>1</sup> and James E. Wells<sup>2</sup>

<sup>1</sup>Department of Chemistry and Physical Sciences, Quinnipiac University, Hamden, CT

<sup>2</sup>W. M. Keck Science Department of Claremont McKenna, Pitzer, and Scripps Colleges, Claremont, CA

The Royal Swedish Academy of Sciences has awarded three physicists the 2018 Nobel Prize in Physics for their “groundbreaking inventions in the field of laser physics.” Half of the prize was awarded to Arthur Ashkin for the development of optical tweezers, a technique that uses radiation pressure from focused laser light to trap, levitate, and move matter. The other half of the prize was shared by Donna Strickland and Gérard Mourou for their pioneering work on an amplification protocol called Chirped Pulse Amplification, which is now used in nearly all high-intensity ultrashort pulsed laser systems.

## Optical Tweezers

Arthur ‘Art’ Ashkin was born September 2, 1922, making him the oldest Nobel Laureate ever at 96-years-old. An alumnus of Columbia College, he received his PhD from Cornell University in 1952. From there he went to work at Bell Labs in Holmdel, New Jersey, where he remained until retiring in 1992. However, Dr. Ashkin is still active in research and is planning to submit a paper to Science on solar energy [1]. Dr. Ashkin is a pioneer in the practical applications of radiation pressure and optical trapping.

In 1969, Dr. Ashkin saw the potential in radiation pressure for manipulating particles when he observed that in a 1-W laser beam low-mass particles may experience accelerations of  $\sim 10^5 g$ . In that same year, he showed that small, transparent particles could be pushed via radiation pressure due to collisions with photons. However, he found an unexpected effect as well [2, 3] – the spheres were pulled into the high intensity region at the center of the beam! The technique is called an optical dipole trap or optical twee-

ers, because the laser beam can precisely grab a particle and manipulate it [5]. The dipole force is enhanced in the optical tweezers by using a microscope objective to focus the beam to a small area, increasing the intensity gradient and therefore the magnitude of the gradient force.

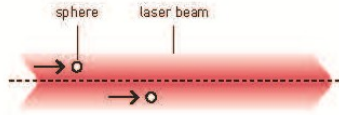
In the Mie scattering regime, where a particle’s size is large compared to the wavelength of the trapping laser, the mechanism of the dipole trap can be explained using ray optics. For the particle labelled “sphere” in Fig. 1, assuming that it has an index of refraction higher than the surrounding medium, light incident on the bottom half of the sphere will refract away from the center of the beam. By conservation of momentum, the sphere will be pushed towards the center of the beam. Light incident on the top half will push the sphere away from the center. Since the beam is more intense in the center than at the edges, the net force points towards the center of the beam. The high intensity region in the center of the beam is a point of stable equilibrium for the particle. If the sphere moves away from the center it will experience a restoring force pointing back to equilibrium. [4].

In the Rayleigh regime, where the trapped particles have a diameter  $2r$  much less than  $\lambda$  the wavelength of the laser light, wave optics must be used, but the general results are the same. In the direction of the beam, a particle will experience a force  $F_{\text{scat}} = n_{\text{med}} P_{\text{scat}}/c$ , where  $n_{\text{med}}$  is the index of refraction of the surrounding medium (often water when trapping biological material),  $P_{\text{scat}}$  is the scattered power, and  $c$  is the speed of light in a vacuum. This scattering force can be written in terms of the intensity of the beam  $I_0$  and the ratio of the index of refraction in the medium to the index of refraction of the trapped

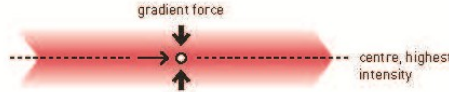


## Ashkin creates his light trap

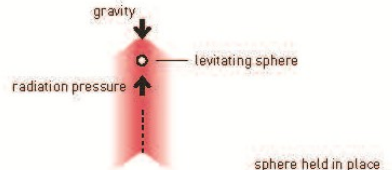
1 Small transparent spheres are set in motion when they are illuminated with laser light. Their speed corresponds to Ashkin's theoretical estimation, demonstrating that it really is radiation pressure pushing them.



2 One unexpected effect was the gradient force that pushes the spheres towards the centre of the beam, where the light is most intense. This is because the intensity of the beam decreases outwards and the sum of all the forces pushing the spheres sends them towards its centre.



3 Ashkin makes the spheres levitate by pointing the laser beam upwards. The radiation pressure counteracts gravity.



4 The laser beam is focused with a lens. The light captures particles and even live bacteria and cells in these optical tweezers.



© Johan Jarnestad/The Royal Swedish Academy of Sciences

Figure 1: An illustration of the experimental steps leading to the creation of the optical tweezers. Dr. Ashkin first showed that the radiation pressure could exert a force large enough to affect macroscopic objects. It was during this experiment that the effect of the gradient force, which pulls the spheres into high intensity regions of the beam, was discovered. By turning the beam vertical, Dr. Ashkin created a trap that could exert a force on the order of the weight of the particle. This trap relied on the balance of the gravitational force and the scattering force to provide stability, which limited its effectiveness. Finally, by focusing the beam, Dr. Ashkin created the optical tweezers, a trap that can exert forces many thousands of times the weight of the trapped particle. ©Johan Jarnestad/The Royal Swedish Academy of Sciences

object  $m = n_{\text{obj}}/n_{\text{med}}$  as

$$F_{\text{scat}} = \frac{I_0}{c} \frac{128\pi^5 r^6}{3\lambda^4} \left( \frac{m^2 - 1}{m^2 + 2} \right)^2 n_{\text{med}}. \quad (1)$$

The gradient force in the Rayleigh regime is

$$\begin{aligned} \vec{F}_{\text{grad}} &= -\frac{n_{\text{med}}}{2} \alpha \nabla |\vec{E}|^2 \\ &= -\frac{n_{\text{med}}^3 r^3}{2} \left( \frac{m^2 - 1}{m^2 + 2} \right) \nabla |\vec{E}|^2 \end{aligned} \quad (2)$$

where  $\alpha$  is the polarizability of the trapped particle. The gradient force will be a restoring force

when  $m$  is greater than one, i.e., the index of refraction of the particle must be greater than the index of the medium [4].

A sphere in the Rayleigh regime will be stably trapped when the ratio of the gradient force to the scattering force is greater than one at the maximum value of the axial intensity gradient [4]. For a Gaussian beam of spot size  $w_0$ , the maximum occurs at  $z = \pi w_0^2 / \sqrt{3} \lambda$  and

$$\frac{F_{\text{grad}}}{F_{\text{scat}}} = \frac{3\sqrt{3}}{64\pi^5} \frac{n_{\text{med}}^2}{\left( \frac{m^2 - 1}{m^2 + 2} \right)} \frac{\lambda^5}{r^3 w_0^2} \geq 1. \quad (3)$$

The principles of optical tweezers have been used successfully to trap atoms and molecules in two- or three-dimensional optical lattices, facilitating near total control over their interactions.

In 1986, Art Ashkin and Steven Chu demonstrated the first optical trapping of neutral atoms [6]. The picture of the trapped atoms included in this paper was the first color figure published in *Physical Review Letters*. Further research on neutral atom trapping led to a Nobel Prize for Steven Chu in 1997 [7].

The following year Art Ashkin and Joseph Dziedzic demonstrated the manipulation of tobacco mosaic virus using the optical tweezers [2, 8, 9]. They also observed small moving objects among the stationary viruses. Bacteria had been accidentally trapped as well, but they were soon optically cut by the laser beam. Once the laser was switched from visible to near-infrared wavelengths, bacteria could be trapped and kept alive for a long duration.

The trapping wavelength for biological particles depends on several factors. The first is preventing heating of the specimen by light absorption and the subsequent damage to the sample. Since most biological samples are observed in water, the absorption spectrum of water constrains the choice of wavelengths. Lastly, the characteristics of the objective lens must also be considered – both in terms of transmission and aberration correction. These considerations lead to most optical tweezers using lasers with wavelengths between  $\sim 850$  nm and 1064 nm [10].

The ability to manipulate bacteria, viruses, DNA, proteins, and even the organelles within cells without damage has led to a vast field of research into understanding how forces and torques affect life on the cellular level [2, 11]. For example, optical tweezers have been used to measure the swimming force of bacteria, the strength of motor proteins, the elasticity of DNA, and the torque required to unravel DNA strands. Optical tweezers are being combined with other techniques that probe single biomolecules, giving us unprecedented access to the workings of the cell and its organelles [11].

## Chirped Pulse Amplification

Prof. Gérard A. Mourou was born and raised in France, earning his PhD from Pierre and Marie Curie University in Paris in 1973. After completing a postdoc at University of California, San Diego, he became a professor at the University of Rochester in New York in 1977. In the mid 1980s, Prof. Mourou supervised a doctoral student, Donna T. Strickland, who earned her PhD in Optics from the University of Rochester in 1989. She is now a professor at the University of Waterloo in her childhood province of Ontario, Canada. In 1985, the first paper she wrote in graduate school [12] would revolutionize ultrafast laser technology and make her the third woman to be awarded a Nobel prize in Physics. Prior to 2018, only two other women had been awarded the prize, Maria Goeppert Mayer in 1963 for developing the nuclear shell model and Marie Curie in 1903 for the theory of radioactivity, respectively.

In Ref. [12] Prof. Mourou and his then graduate student Strickland published a technique for amplifying laser pulses known as chirped pulse amplification (CPA). A similar technique had been used for radar [13], but Ref. [12] was the first attempt within the optical regime. The development of CPA was a side project for Strickland, since her research on multiphoton ionization required higher intensity laser pulses than were commercially available at the time [14].

Today, ultrashort (sub-nanosecond) lasers have applications spanning the atomic and macroscopic regimes. In the atomic regime, the high intensity of a laser pulse creates a strong electric field that is used to investigate atomic and molecular ionization, to offer quantum-limited control over molecular processes, and to drive nuclear fusion reactions. Ultrashort pulses are also used to resolve the sub-nanosecond dynamics of molecular processes, such as molecular vibrations, effectively acting like a high-speed camera.<sup>1</sup> In the macroscopic regime, laser pulses are commonly used for precision machin-

<sup>1</sup>In this analogy, the reciprocal of the short pulse-



ing of materials, such as metal, ceramics, plastics, and biological tissue. For example, the now commonplace laser-assisted in-situ keratomileusis (LASIK) procedure uses femtosecond laser pulses created with CPA to perform eye surgery.

A laser pulse's electric field can be thought of as a superposition of many continuous waves (CW) at different frequencies centered at a carrier frequency  $\omega_0$  with a bandwidth  $\Delta\nu = \Delta\omega/(2\pi)$ . At a fixed location, the superposition of these waves creates a Gaussian shaped pulse with a temporal dependence of

$$\mathcal{E}(t) = \left( \mathcal{E}_0 e^{-2(t/\tau)^2} \right) e^{i\phi(t)}, \quad (4)$$

where  $\mathcal{E}_0$  is the peak electric field amplitude,  $\tau$  is the  $1/e^2$  power level, and the total phase is  $\phi(t) \approx \omega_0 t - \phi_0(t)$ . The different frequency components have a temporal phase of  $\phi_0(t)$ . In Eq. (4), the first term in parenthesis characterizes the shape of the pulse amplitude called the envelope. The second term describes the fast wiggles of the electric field within the envelope, depicted in step 1 of Fig. 2. The instantaneous frequency of the electric field's wiggles can be defined as

$$\omega_{\text{in}} \equiv \frac{d\phi}{dt} \approx \omega_0 - \frac{d\phi_0}{dt}. \quad (5)$$

Laser cavities support longitudinal modes, like standing waves on a string, each with a unique frequency. In CW single-mode operation, the cavity is designed to lase in a single longitudinal mode. For pulsed lasers, many frequency components are desired and the cavity may support  $\sim 10^6$  longitudinal modes.

If each mode has a random temporal phase  $\phi_0$ , then the power is constant with time. However, if the temporal phase between different modes is fixed or mode locked,  $d\phi_0/dt = 0$ , then the superposition of the modes creates an electric-field pulse that is considered unchirped. In this case, the pulse is as narrow as possible, limited by the uncertainty principle, with a time-bandwidth

duration is like the high frame rate of a slow-motion camera.

product of  $\Delta t \Delta\nu \sim 1/2$ . Alternatively, if the pulse is linearly chirped, then the temporal phase  $\phi_0 = \beta t^2$ , where  $2\beta$  is the chirp rate. The term "chirp" comes from the sound birds make, which results from a fast sweep over many acoustic frequencies.

According to Eq. (5), the instantaneous frequency of the chirped electric field is  $\omega_{\text{in}} = \omega_0 - 2\beta t$ , which results in a decrease in frequency over the duration of the pulse. The continuously changing frequency is called a negative (down) chirp (as seen in step 2 of Fig. 2). Effectively, at a fixed location, the blue wavelengths will lag behind the red ones in time. Positive (up) chirp is the reverse situation.

The peak intensity of a laser pulse is defined as the peak power per unit area. The peak power is  $P = E/\Delta t$ , where  $E$  is the total energy per pulse and  $\Delta t$  is the pulse duration. For a fixed beam size, the peak intensity can be increased by increasing the energy per pulse, decreasing the pulse duration, or both. To narrow the pulse in time a broader amplification-bandwidth  $\Delta\nu$  is required, which is dependent on the choice of gain medium.

Unfortunately, practical problems arise if direct brute-force amplification of the pulse energy is attempted at high intensity. One example is the Optical Kerr Effect, where nonlinear terms in the medium's electric susceptibility cause the refractive index to become dependent on the laser intensity. The total refractive index can be approximated as  $n \approx n_0 + n_2 I$ , where  $n_0$  is the linear refractive index  $n_2$  is the second-order nonlinear laser-induced refractive index, and  $I$  is the laser intensity. Consequently, a laser pulse with a Gaussian spatial mode creates a Gaussian shaped index-of-refraction gradient, which in turn creates a gradient-index lens.<sup>2</sup> If the pulse exceeds a critical beam power such that the focusing of the laser-induced lens overcomes the diffractive spreading of the beam, then a runaway effect called self-focusing can arise [5]. By

<sup>2</sup>Unlike a conventional lens that has a single index of refraction with variable thickness, a gradient-index lens has a single thickness and a variable index of refraction.

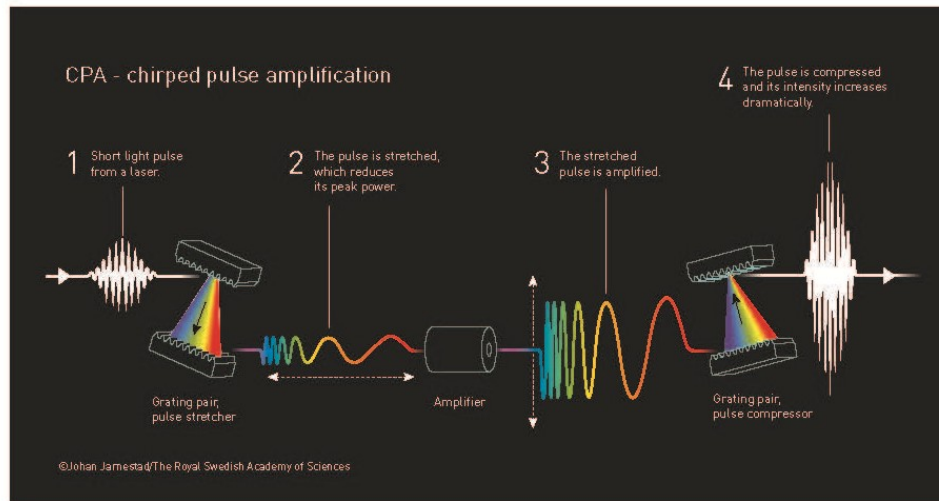


Figure 2: Schematic of the CPA protocol. Initially, a short light pulse from a laser goes through a double diffraction-grating configuration that chirps the pulse in time, lowering the peak power of the pulse. The low-power pulse can then safely pass through an optical amplifier without risk of damage to the amplifier or degrading the spatial mode of the pulse. Next, the amplified pulse is compressed using another pair of diffraction gratings, yielding a pulse with greater total energy and higher intensity. ©Johan Jarnestad/The Royal Swedish Academy of Sciences

virtue of being focused, the beam becomes more intense and creates an even stronger lens, distorting the beam's spatial mode and eventually ionizing the medium. Gain media typically have  $n_2 \sim 10^{-7} \text{ cm}^2/\text{GW}$  and directly amplifying pulses with  $P \gtrsim 1 \text{ MW}$  results in self-focusing [5].

Additional issues arise from laser-induced mechanical damage to the gain medium, cavity optics, and their coatings. The strong electric fields of the high-intensity laser light causes dielectric breakdown and thermal heating. At  $\sim 500 \text{ MV/m}$  optical materials and gain media undergo dielectric breakdown, which limits the intensity to  $\sim 10 \text{ GW/cm}^2$ .

The CPA technique, as depicted in Fig. 2, increases the peak intensity by amplifying the total energy per pulse outside of the laser cavity to avoid damaging the amplifying medium. The protocol starts with an ultrashort, low-energy seed pulse (shown as stage 1 in Fig. 2).<sup>3</sup>

<sup>3</sup>In their original manuscript [12], Prof. Mourou and Strickland use a mode-locked neodymium-doped yttrium

Next, two reflection gratings diffract the pulse so that it becomes a linear, negative chirped pulse. The double grating separates all of the pulse's frequency components spatially in such a way that the optical path length of the red light is shorter than that of the blue light. The pulse is now stretched out in time by a factor of  $10^5$ , so the blue components lag behind the red [14]. At that point, the pulse has a much larger width  $\tau \propto \Delta t$  and a proportionally smaller peak power.

The low-power laser pulse can safely be amplified without risk of laser-induced damage within the amplifying medium. An optical amplifier, like a laser, relies on stimulated emission within a gain medium, but the cavity is not designed to provide the optical feedback necessary for lasing [5]. As such, the amplifying medium is often pumped, typically by another laser, and the seed pulse passes through the amplifier a finite num-

ber of times. The first CPA experiment used a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser centered at a wavelength 1060 nm. Today, Titanium doped sapphire lasers (Ti:sapphire) centered at a wavelength 800 nm are preferred because they create narrower pulses and are generally less temperamental to maintain and operate.



ber of times before exiting. The original CPA setup [12] used a regenerative amplifier consisting of Nd doped glass. A polarizing beamsplitter and a voltage-controlled waveplate (Pockels cell) both “frustrate” the lasing [12] in the amplifier and injects/ejects the beam out of the amplifier. The Pockels cell can quickly manipulate the laser light’s polarization to eject the light after the beam takes  $\approx 100$  passes [12]. An alternative scheme, called a multi-pass amplifier, uses multiple mirrors and/or an oversized mirror to bounce the beam through the amplifier a few times ( $\sim 10$ ) before exiting the amplifier. In the end, a pulse can be amplified by a factor of  $10^6$  [12] or more.

Finally, the amplified pulse (shown as stage 3 in Fig. 2) passes through a double grating compressor [15], applying a positive chirp that compensates for the previously added negative chirp. The output is once again a mode-locked pulse, but now with greater energy, and thus, greater intensity!

Because the CPA is external to the laser that created the original seed pulse, CPA is laser-system independent. Today, CPA is still the standard protocol for making ultrashort high-intensity laser pulses in commercial laser systems, tabletop experiments at universities, and large laser facilities like the Laboratory for Laser Energetics at the University of Rochester and the Lawrence Livermore National Laboratory. Currently, the HERCULES 300 TW laser at the University of Michigan uses CPA to create the highest focused laser-intensity in the world ( $I \sim 10^{13}$  GW/cm<sup>2</sup>), according to the Guinness Book of World Records. The HERCULES boasts an intensity equivalent to  $\sim 10^{23}$  suns at one earth-sun distance.

The pioneering work of Dr. Ashkin, Prof. Mourou, and Prof. Strickland has significantly advanced laser physics, atomic, molecular, and optical physics, and biology. Optical tweezers and CPA help us continue to push the boundaries of our control over matter, paving the way toward the next generation of laser-tool inventions.

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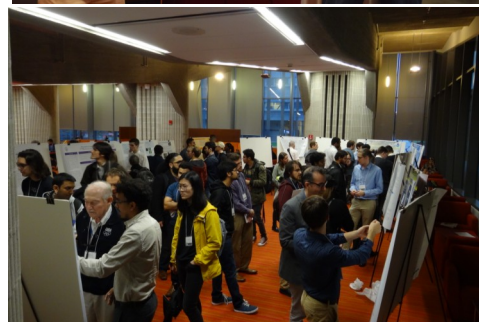
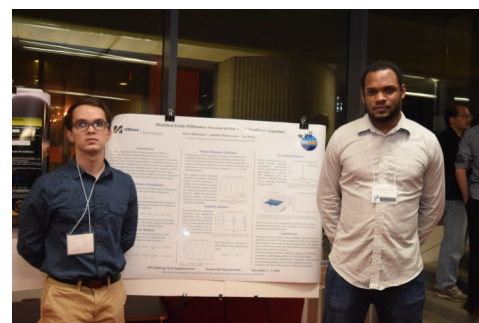
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## Thank you to UMASS Dartmouth, and welcome to Spring at **Springfield College**



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