Photonics at Thermodynamic Limits (PTL)
EFRC Director: Jennifer Dionne
Lead Institution: Stanford University
Class: 2018 – 2022

Mission Statement*: To achieve photonic operations at thermodynamic limits by controlling the flow of photons, electrons, and phonons in atomically-architected materials, enabling entirely new energy conversion systems.*

Thermodynamic cycles enable optimized performance of nearly every energy conversion device that underpins advanced economies. While most thermodynamic cycles rely on a classical fluid, photons can also be used to drive thermodynamic cycles. The “Photonics at Thermodynamic Limits” (PTL) EFRC strives to achieve photonic operations at thermodynamic limits by controlling the flow of photons, electrons, and phonons in atomically-architected materials, enabling entirely new energy conversion systems. Such photon-based Carnot cycles offer remarkable opportunities for energy conversion, including all-optical energy-storage, optical refrigeration, optical rectification, power-generating windows that absorb light yet remain transparent, and beyond von-Neumann information architectures. Realizing photonic thermodynamic cycles requires new optical materials design, synthesis and characterization so that photonic operations – such as absorption, emission, and reflection – can be performed with the highest possible efficiency.

Objectives for 2018-2022

To design new photonic energy systems based on very high radiative efficiency, the PTL EFRC uses theory to guide experiments that are in turn validated by state-of-the-art characterization techniques. We will:

1. Design and develop atomically-precise and ‘beyond-ideal’ materials that perform photonic operations at thermodynamic limits (Research Group 1).
2. Develop transformative characterization methods to correlate structure-to-function with unprecedented spatial and temporal resolution (Research Group 2)
3. Investigate emergent physical phenomena and photonic thermodynamic cycles that arise when photonic processes approach the thermodynamic limits of photonic operations (Research Group 3).

Center Research Team and Scientific Organization

To achieve our mission, we have united leading researchers in layered and nanostructured materials synthesis, electromagnetic theory, first-principles quantum theory of materials, and advanced characterization of excited state phenomena. The Center is organized scientifically into three research groups (RGs) that address scientific themes related to photonics at thermodynamic limits, with each team spanning multiple institutional partners and designed to address our four-year scientific objectives.

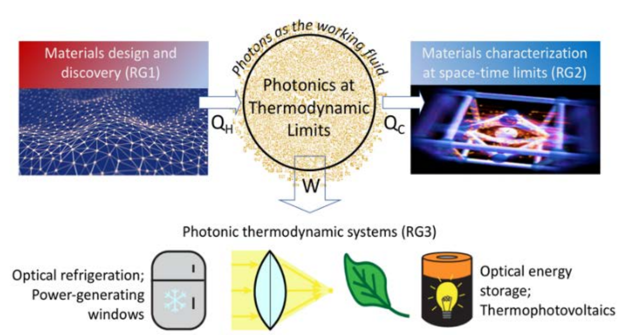

Figure 1: *Schematic overview of our “Photonics at Thermodynamic Limits” Energy Frontier Research Center.*

- **Research Group 1 – Materials Design and Discovery:** Using novel quantum-electro-dynamic and first-principles calculations, the RG1 team is identifying conditions that maximize the useful work of a photonic system, involving energy, phase, momenta, and entropy of photons. In parallel, using state-of-the-art materials chemistry, we are developing nanoparticles and 2D materials with near-unity quantum yields, ultra-high-conductivity and reflectivity, and low-power nonlinearities.

- **Research Group 2 – Materials Characterization at Space-Time Limits:** The RG2 team is developing transformative characterization methods that include (1) novel in-operando characterization platforms based on optical microscopy within a transmission electron microscope (OTEM); (2) ultrafast stimulated emission depletion (STED) optical microscopy; (3) photothermal deflection spectroscopy; and (4) single particle ultrafast diffraction leveraging the unique facilities at SLAC National Accelerator Laboratory.
- **Research Group 3 – Photonic Thermodynamic Systems:** The RG3 team will investigate emergent physical phenomena and photonic thermo-dynamic cycles that arise when photonic processes approach the thermodynamic limits of photonic operations, including radiative cooling, all-optical energy storage, power-generating windows, and thermophotovoltaics.

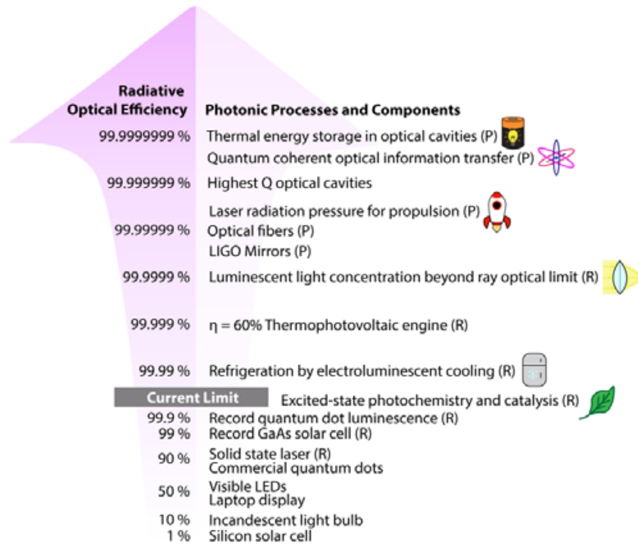

Figure 2: *Passive (P) and Active radiative (R) systems that become possible with increasingly high optical efficiency.*

Selected Accomplishments

Our long-term goal is to design photonic conversion systems for energy and information that operate at thermodynamic limits, and to share our research with technologists, policymakers and the public to maximize the societal impact of our EFRC. Selected accomplishments to date include:

- Developed new excited state theoretical methods to describe electron/phonon and photon/phonon interactions in nanoparticles and 2D materials (RG1).
- Achieved record conversion efficiency in a regenerative thermophotovoltaic system, incorporating photonic design to reuse low-energy photons (RG3).
- Realized near-unity luminescence in core/shell quantum dots (RG1) and characterized their quantum yield with high-precision using photothermal threshold quantum yield measurements (RG2).
- Designed novel heterostructures of two-dimensional transition metal dichalcogenides (RG1).
- Correlated optical and electron microscopy to identify the role of structure on quantum emission in two-dimensional materials (RG2).
- Utilized ultrafast electron diffraction (UED) at SLAC to unravel nanocrystal structural dynamics (RG2).
- Developed new paths to non-reciprocal emission and transmission (RG3).

Photonics at Thermodynamic Limits (PTL)	
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