Vision with Heat and Light

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(Visible) Light Transport

Absorbed Light Raises Temperature

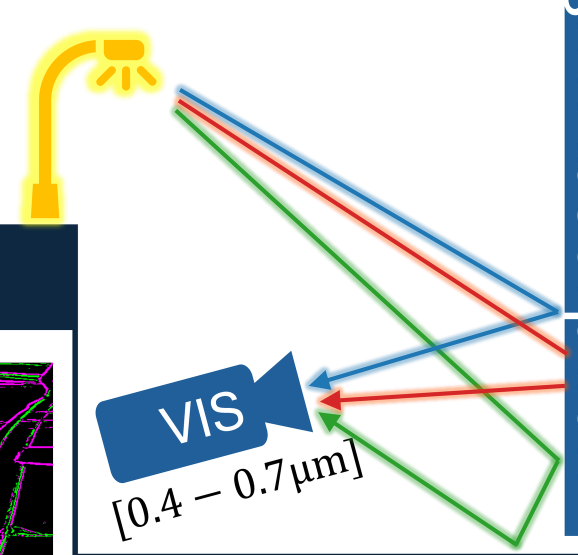
Mainstream Vision models:

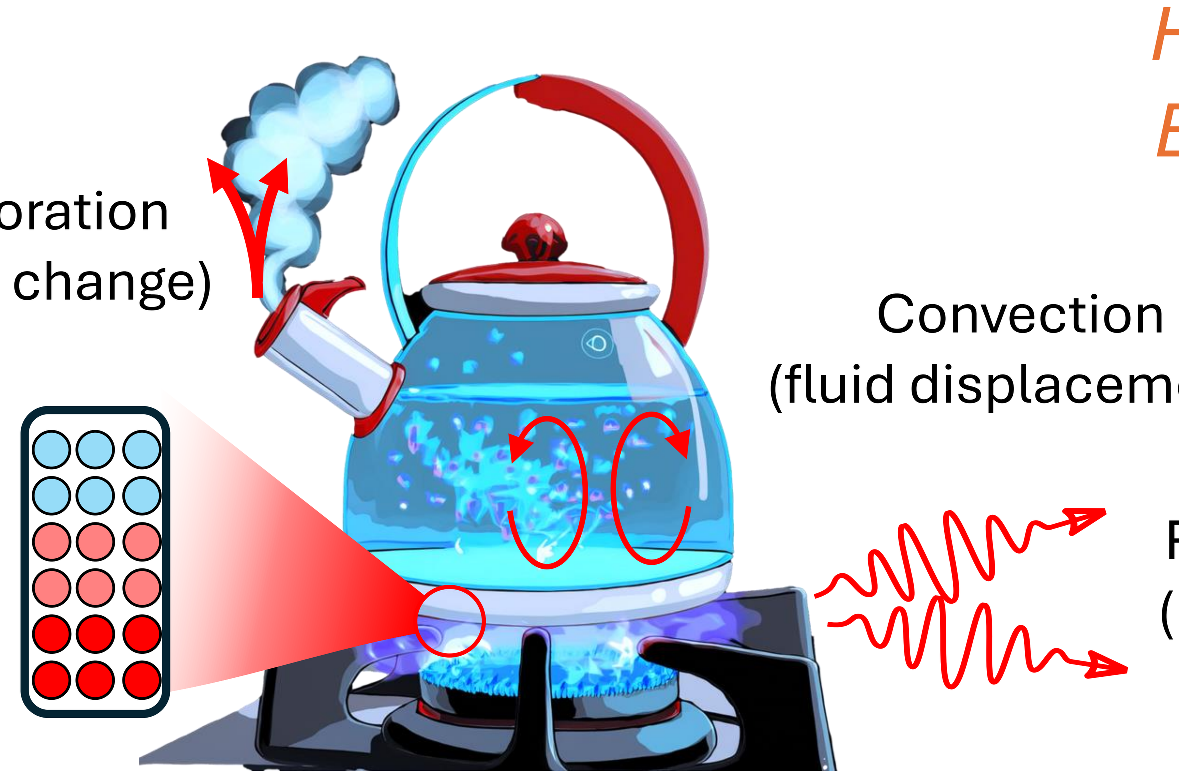
- Direct Illumination ✓
- Scattering Media ✓
- Global Illumination ✓
- Absorbed Light ?

Light-to-Heat

$$\underset{\text{Intensity}}{\text{VIS}}\quad I_v(\mathbf{x}) = \frac{\overbrace{\rho(\mathbf{x})}^{\text{albedo}}}{\pi}\underbrace{\gamma}_{\text{camera gain}}\overbrace{\eta^*(\mathbf{x})}^{\text{scene irradiance}}$$

$$S(\mathbf{x}) = \underbrace{(1-\rho(\mathbf{x}))\eta^*(\mathbf{x})}_{\text{net absorbed energy}}$$

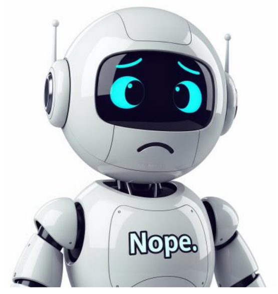




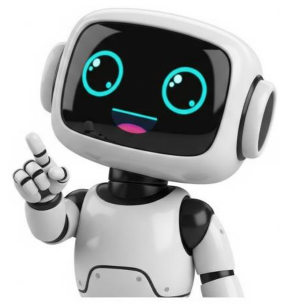
(Thermal) Light Transport

Hotter Surfaces Emit More Light

Thermal cameras measure temperature – Nope.

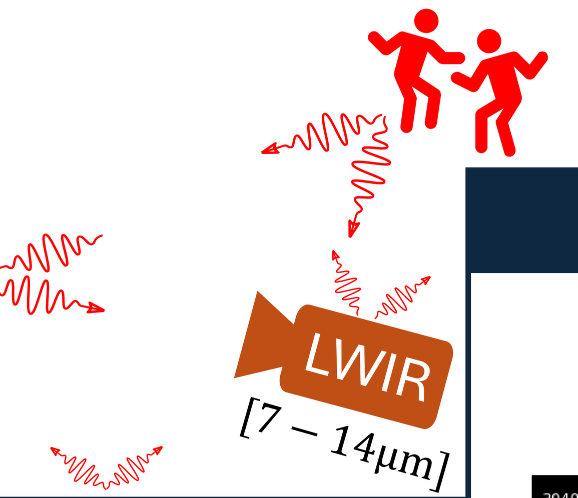


Thermal cameras measure *radiance* – Yes!



Heat-to-Light

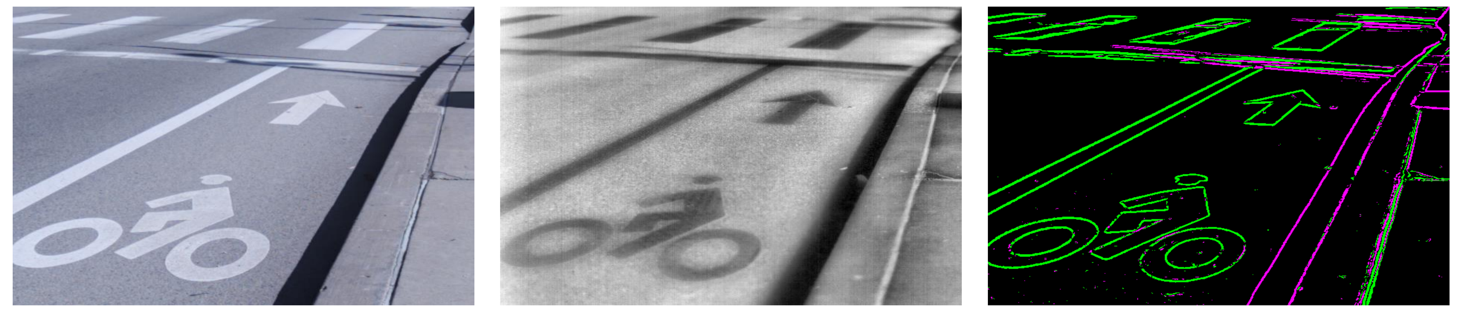
$$\underset{\text{Intensity}}{\text{LWIR}}\quad I_l(\mathbf{x}, t_n) = \overbrace{\epsilon}^{\text{emissivity}}\underbrace{U}_{\text{camera response}}(\overbrace{T(\mathbf{x}, t_n)}^{\text{temperature}}) + \overbrace{U_s}^{\text{surr. radiance}}$$



Heat Transport (independent of λ)

$$\underbrace{C_v}_{\substack{\text{heat}\\\text{capacity}}}\underbrace{\delta_z}_{\text{thickness}}\frac{\partial T(\mathbf{x},t)}{\partial t} = \overbrace{S(\mathbf{x})}^{\text{source intensity}} + \underbrace{\sigma}_{\substack{\text{Stefan-Boltzmann}\\\text{constant}}}\overbrace{\epsilon}^{\text{emissivity}}(\underbrace{T_s^4}_{\substack{\text{surrounding}\\\text{temp.}}} - \overbrace{T(\mathbf{x},t)^4}^{\text{surface temperature}}) + \underbrace{h_c}_{\substack{\text{convection}\\\text{coeff.}}}(\underbrace{T_a}_{\text{air temp.}} - T(\mathbf{x},t)) + \delta_z\underbrace{\kappa}_{\substack{\text{thermal}\\\text{conductivity}}}\underbrace{\Delta_{\mathbf{x}}}_{\substack{\text{Laplace}\\\text{operator}}}T(\mathbf{x},t)$$

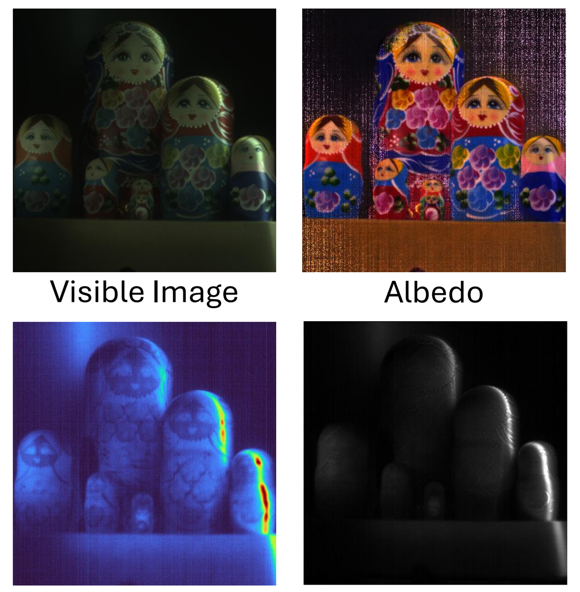
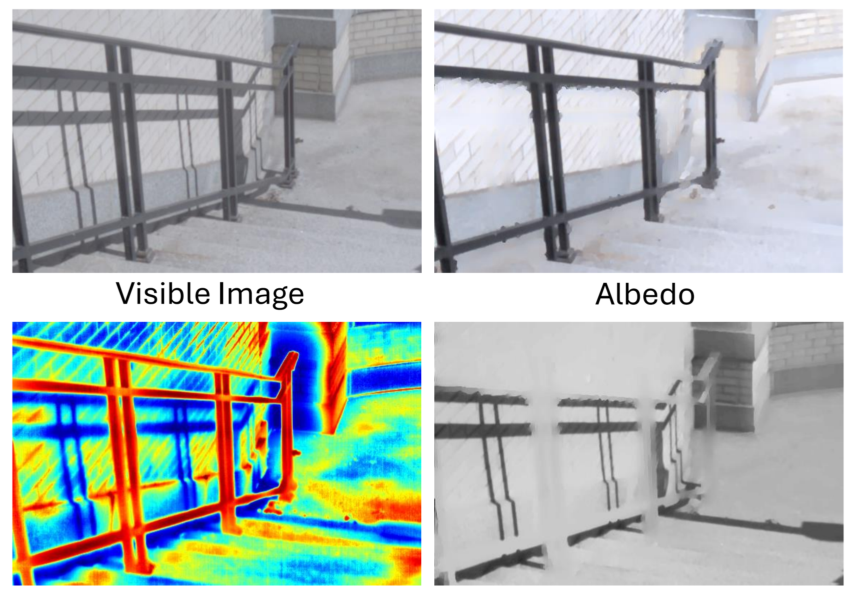
Intrinsic Image Decomposition (IID)



Visible Image · Thermal Image · Albedo / Shading edge

Brighter + Hotter = Receives More
Brighter + Cooler = Reflects More

Visible Image

+ Thermal Video	+ Thermal Image
	
Visible Image, Albedo, Absorbed Light, Shading	Visible Image, Albedo, Thermal Image, Shading

Single-view IID is *well-posed* with absorbed light.

Albedo $\rho(\mathbf{x}) = \dfrac{\pi I_v(\mathbf{x})}{\pi I_v(\mathbf{x}) + \zeta S(\mathbf{x})}$ Shading $\eta(\mathbf{x}) = \pi I_v(\mathbf{x}) + \zeta S(\mathbf{x})$

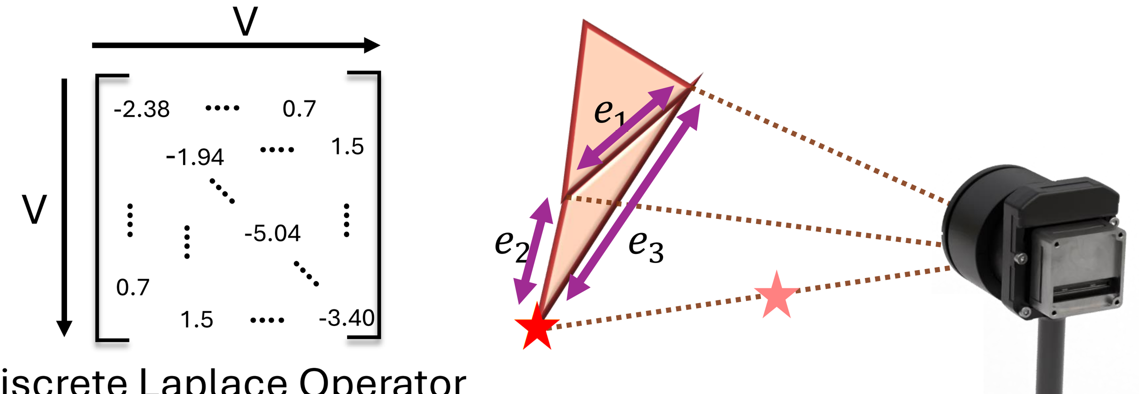
Shape from Heat Conduction

Thermal Video is a Linear System

$$\underbrace{\begin{bmatrix} \frac{T_1 - T_0}{dt} & -T_1 & (T_1 - T_s) & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \frac{T_n - T_{n-1}}{dt} & -T_n & (T_n - T_s) & 1 \end{bmatrix}}_{\text{Known}} \underbrace{\begin{bmatrix} \text{heat capacity} \\ \text{Laplace operator} \\ \text{convection coeff.} \\ \text{source intensity} \end{bmatrix}}_{\text{Unknowns}} = \underbrace{\begin{bmatrix} 4\sigma\epsilon(T_s^4 - T_s^3 T_1) \\ \vdots \\ 4\sigma\epsilon(T_s^4 - T_s^3 T_n) \end{bmatrix}}_{\text{Known}}$$

Time

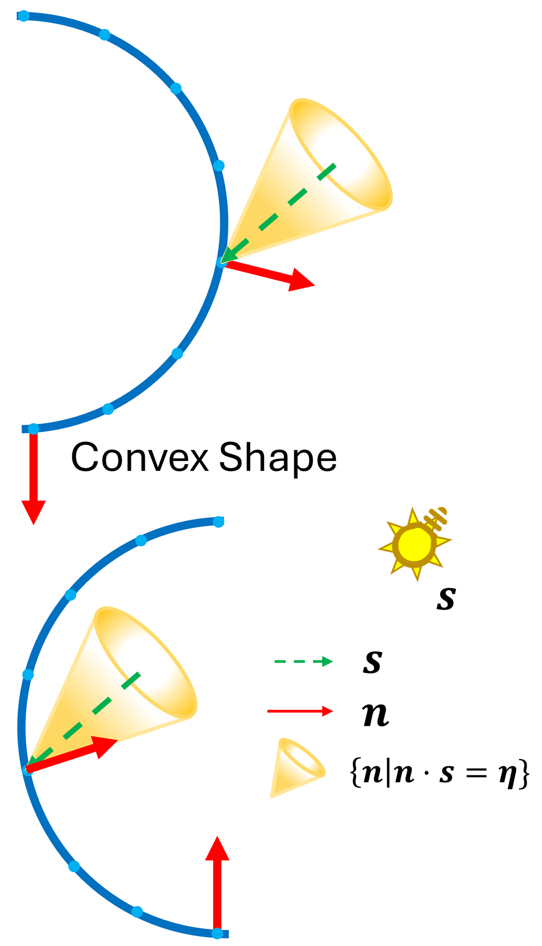
Laplacians encode Curvature via Edge Lengths

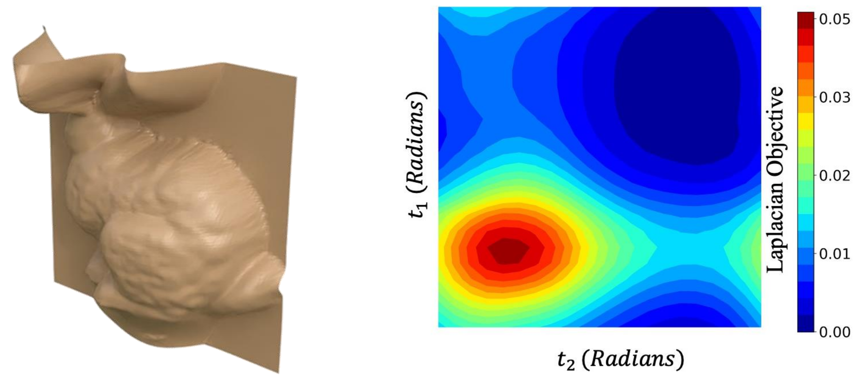


Discrete Laplace Operator

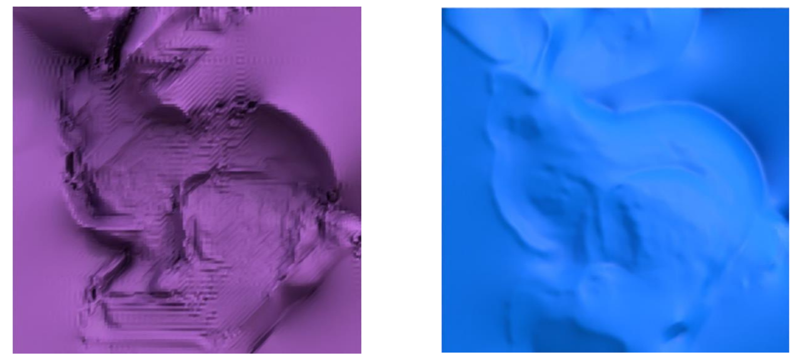
Shape from Laplacian and Shading

Laplacians have		Shading has		
Local Binary Ambiguity	∩	Per-pixel Cone Ambiguity	=	Two Global Solutions





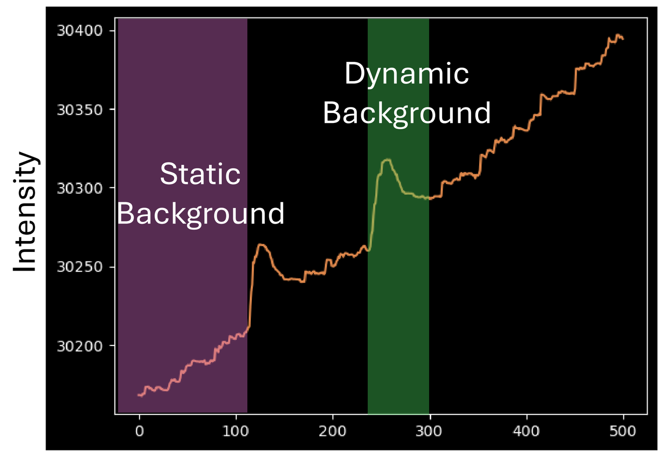
Ours · Laplacian costmap when searching over 2 cones



Shape from Laplacian · Shape from Shading

Reflection-Emission Separation

Accurate Temperature requires Accurate Emissivity



$$I_{\lambda_1}(t) = \epsilon_1 U_1(T_o(t)) + (1-\epsilon_1)U_1(T_b(t))$$
$$I_{\lambda_2}(t) = \underbrace{\epsilon_2}_{\text{emissivity}} U_2(\underbrace{T_o(t)}_{\text{obj. temp.}}) + (1-\epsilon_2)U_2(\underbrace{T_b(t)}_{\text{bkg. temp.}})$$

Static bkg. objects: $\dfrac{\partial I_{\lambda_1}/\partial t}{\partial I_{\lambda_2}/\partial t} \propto \dfrac{\epsilon_1}{\epsilon_2}$

Movin bkg. objects: $\dfrac{\partial I_{\lambda_1}/\partial t}{\partial I_{\lambda_2}/\partial t} \propto \dfrac{1-\epsilon_1}{1-\epsilon_2}$