A layer-based restoration framework for variable-aperture photography

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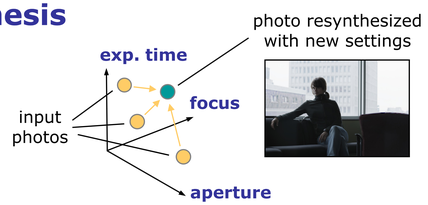
Motivation: Post-capture resynthesis

In conventional photography, camera settings are fixed at capture time & can't be modified later.

Given a small # of photos taken from the same viewpoint, provide the means to synthetically control **exposure time**, **focus setting**, and **aperture**.

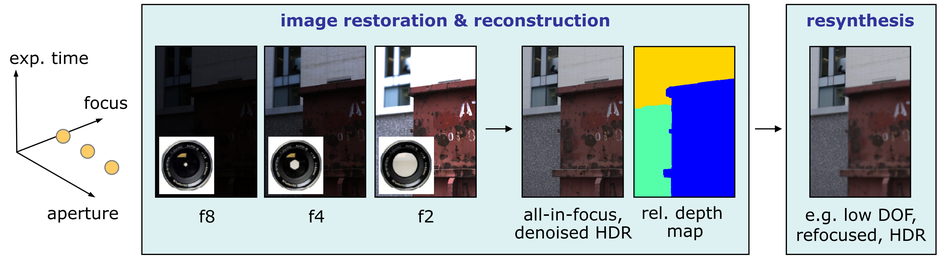


Idea #1: Variable-aperture photography

Input: A few photos captured with different aperture settings & everything else fixed, a.k.a. **aperture bracketing**.

Goal: Recover the
- all-in-focus, denoised high dynamic range (HDR) radiance map &
- layered scene representation

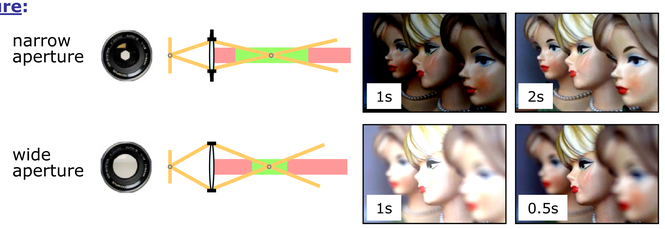
that reproduces the input & allows post-capture resynthesis.



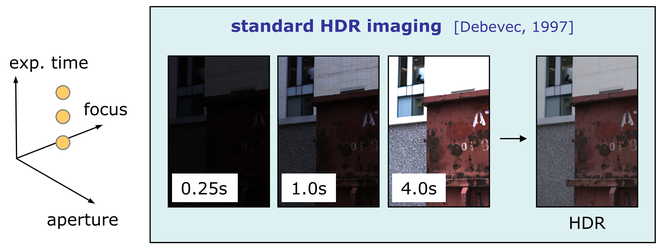
The effect of changing aperture:

Aperture setting simultaneously affects **image brightness** and **defocus**.

For narrow apertures, dark regions are **noisy** and underexposed, etc.



Related work:
- shape-from-defocus based on image restoration [Rajagopalan, 2005]
- layered models for defocus [Favaro, 2003] [McGuire, 2005]
- refocusing using new camera designs [Ng 2005] [Levin, 2007]



Our approach vs. HDR:
- same # input photos
- both denoise output
- our approach lets us modify focus & DOF

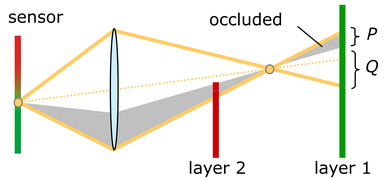
Idea #2: Layered image formation model

Layered scene representation

$$\left(\underbrace{\mathbf{L}}_{\substack{\text{all-in-focus}\\ \text{HDR radiance}}} , \underbrace{\{\mathbf{A}_k\}}_{\substack{\text{layer}\\ \text{assignment}}} , \underbrace{\{\sigma_k\}}_{\substack{\text{per-layer blur levels}\\ \& \text{ ordering}}} \right)$$

radiance map; relative depth map

Thin lens model for defocus [Asada, 1998]
- computationally expensive with occlusion

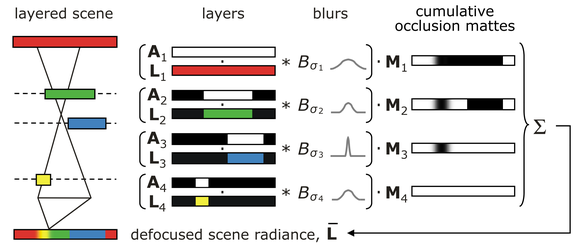


1. Approximate layered defocus:
- blurs layers independently & weighs by visibility
- effective in practice & tractable to invert

Example: contribution of layer 1

$$\text{exact } \mathbf{L}_Q \qquad \text{approx. } \underbrace{\left(\mathbf{L}_P + \mathbf{L}_Q\right)}_{\text{single-layer case}} \cdot \underbrace{\frac{|Q|}{|P|+|Q|}}_{\text{fraction unoccluded}}$$

2. Image formation with approximate layered defocus:
- approximate layered defocus, applied to K layers
- generalizes the matting equation [Blinn, 1982]



3. Simplified scene model (used for estimation):
- represents the scene using multiple layers & a single all-in-focus HDR radiance map
- extends occluded regions using **inpainting**

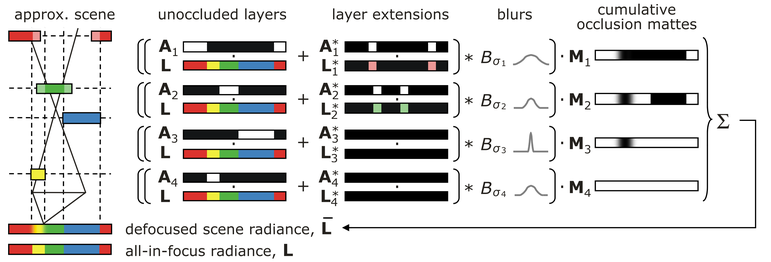


Image restoration method

Input: Photos captured by aperture bracketing, $\mathbf{I}_a$

Goal: Compute $\operatorname{argmin}_{\mathbf{L},\mathbf{A},\sigma} \mathcal{O}(\mathbf{L},\mathbf{A},\sigma)$

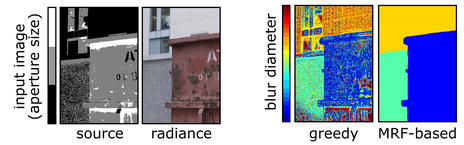
$$\mathcal{O}(\mathbf{L},\mathbf{A},\sigma) = \frac{1}{2}\sum_a \left\| \hat{\mathbf{I}}_a - \min\left(e_a \cdot \overbrace{\bar{\mathbf{L}}(\mathbf{L},\mathbf{A},\sigma)}^{\text{layered defocus model}},\ 1\right) \right\|^2 + \overbrace{\lambda \|\mathbf{L}\|_\beta}^{\text{HDR TV regularization}}$$

$\hat{\mathbf{I}}_a$: linearized input photos; e_a: exposure factors; 1: saturation

Algorithm:

Iterative alternating minimization
- initialize $(\mathbf{L},\mathbf{A},\sigma)$
- **repeat** until convergence:
  - **repeat** 8x:
    - optimize wrt. radiance $\mathbf{L}$ [10 CG steps]
    - optimize wrt. blurs σ [10 CG steps]
  - re-estimate layer assignment $\mathbf{A}$
  - re-estimate layer ordering

Initialization:

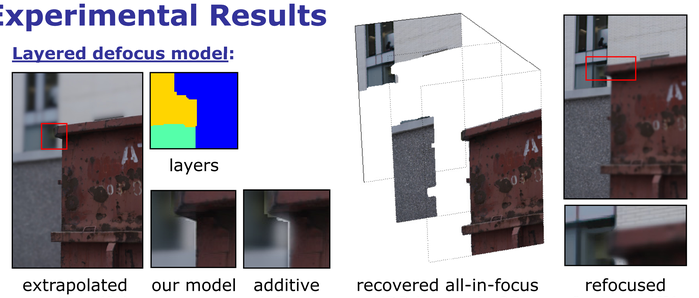


all-in-focus radiance ($\mathbf{L}$)
- per-pixel selection from input, est. SNR

layers and blurs ($\mathbf{A}$,σ)
- shape-from-defocus, hypothesis testing

Experimental Results

Layered defocus model:



Backlit portrait dataset: