Variable Ring Light Imaging
Capturing Transient Subsurface Scattering with An Ordinary Camera

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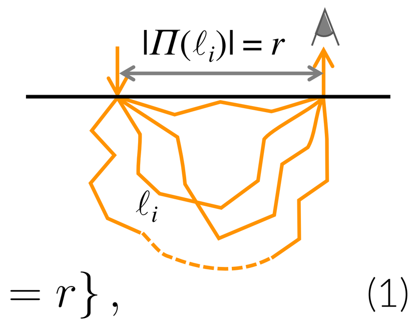
Bounding Subsurface Light Transport

Unlike past transient imaging methods that require special optical instruments and that are limited to scene-wide light transport, **for the first time, we show that transient subsurface light transport can be recovered from the steady-state outer appearance of a surface captured with ordinary imaging components.**

A Natural Lower Bound on Subsurface Light Path Length



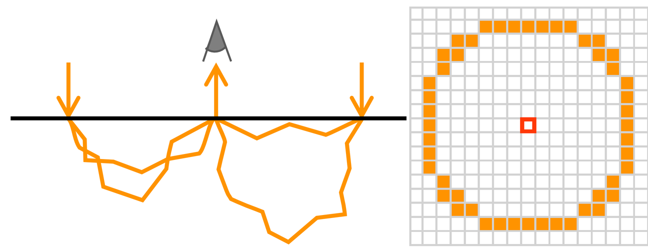
The radiance of a surface point at distance r from an impulse illumination is the sum of the radiance of each light ray, denoted with $L(\cdot)$, parameterized by its path length $|\ell|$:

$$E(r) = \sum_{|\ell_i|\in\mathfrak{L}(r)} L(|\ell_i|) \qquad \mathfrak{L}(r) = \{|\ell_i| \,:\, |\Pi(\ell_i)| = r\}\,, \tag{1}$$

where $\mathfrak{L}(r)$ is the set of path lengths of light rays observed at *surface distance* r and $|\Pi(\ell)|$ is the surface distance each light ray reemerges from. Then,

$\min \mathfrak{L}(r) \geq r$, i.e., the observed light cannot have traveled a shorter distance than the surface distance between the points of incidence and observation.

Ring Light Illumination



For higher image fidelity, we impulse illuminate all surface points at distance r from the surface point of interest whose normalized radiance is

$$E(r) = \frac{1}{K}\sum_k^K E(r_k) = \frac{1}{K}\sum_k^K \sum_{|\ell_i|\in\mathfrak{L}(r_k)} L(|\ell_i|)\,. \tag{2}$$

Transient Subsurface Light Transport from Variable Ring Light Imaging

Consider illuminating the surface with another ring light of radius $r + \Delta r$

$$\mathfrak{L}(r+\Delta r) = \{|\ell_i| \,:\, |\ell_i| \geq r+\Delta r,\ |\Pi(\ell_i)| = r+\Delta r\}\,. \tag{3}$$

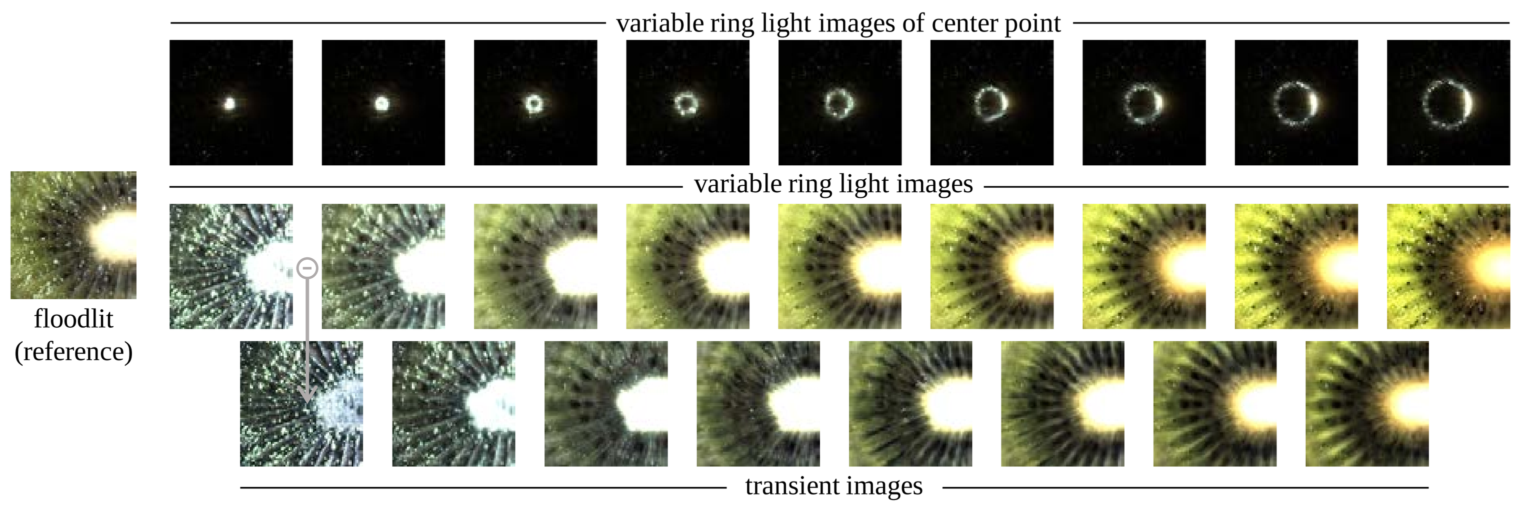
The actual instantiation of the light rays in these two sets Eq. 1 and 3 are disjoint, but we can assume that they approximately overlap for all light rays with path lengths longer than $r + \Delta r$

$$\mathfrak{L}(r) \cap \mathfrak{L}(r+\Delta r) \approx \mathfrak{L}(r+\Delta r)\,. \tag{4}$$

This property holds exactly for homogeneous surfaces and approximately for inhomogeneous surfaces.This allows us to bound the subsurface light path lengths

$$E(r) - E(r+\Delta r) \approx \sum_{|\ell_i|\in\mathfrak{L}(r)\setminus\mathfrak{L}(r+\Delta r)} L(|\ell_i|)\,,\quad \mathfrak{L}(r)\setminus\mathfrak{L}(r+\Delta r) = \{|\ell_i| \,:\, r+\Delta r > |\ell_i| \geq r,\ |\Pi(\ell_i)| = r\}\,.$$

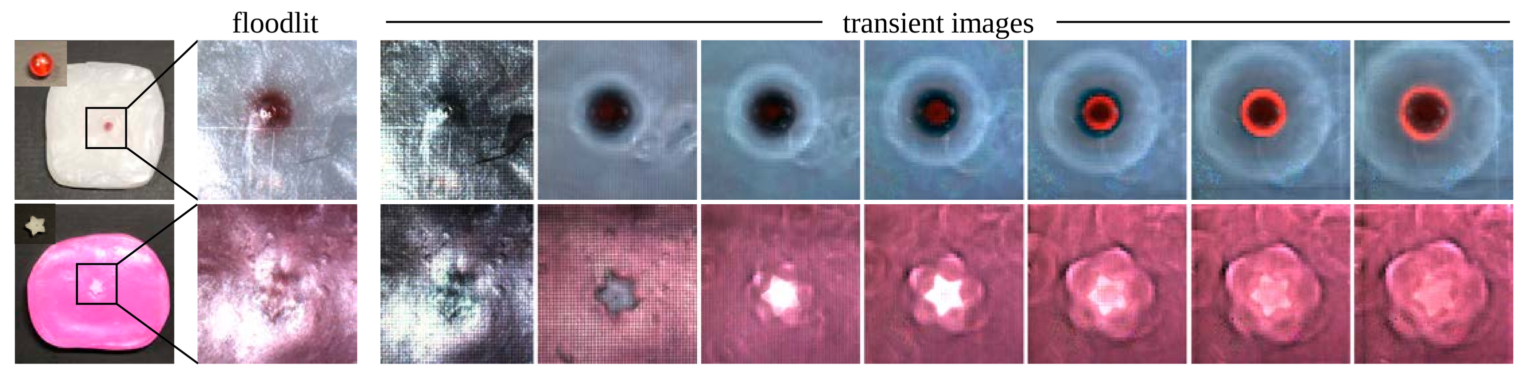
1. Capture impulse illuminated surface points (one image per one point).
2. Reorganize the images into variable ring light images of increasing radius.
3. Compute path-length sampled transient images by taking the differences of variable ring light images across radius increments.



Transient Images

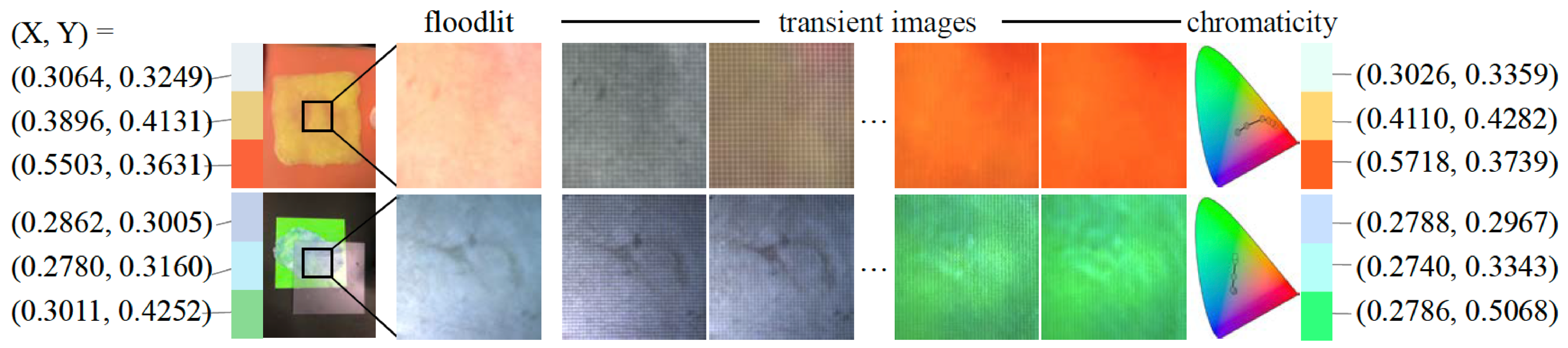
Spatial Subsurface Light Transport

For spatially inhomogeneous subsurface structures, the recovered transient images capture interesting spatial propagation of light as the corresponding ring light radius increases. See, for instance, the star shaped light emanating from the white polymer embedded in pink plastic and its interreflection creating petal-like light propagation shapes as the path length increases.



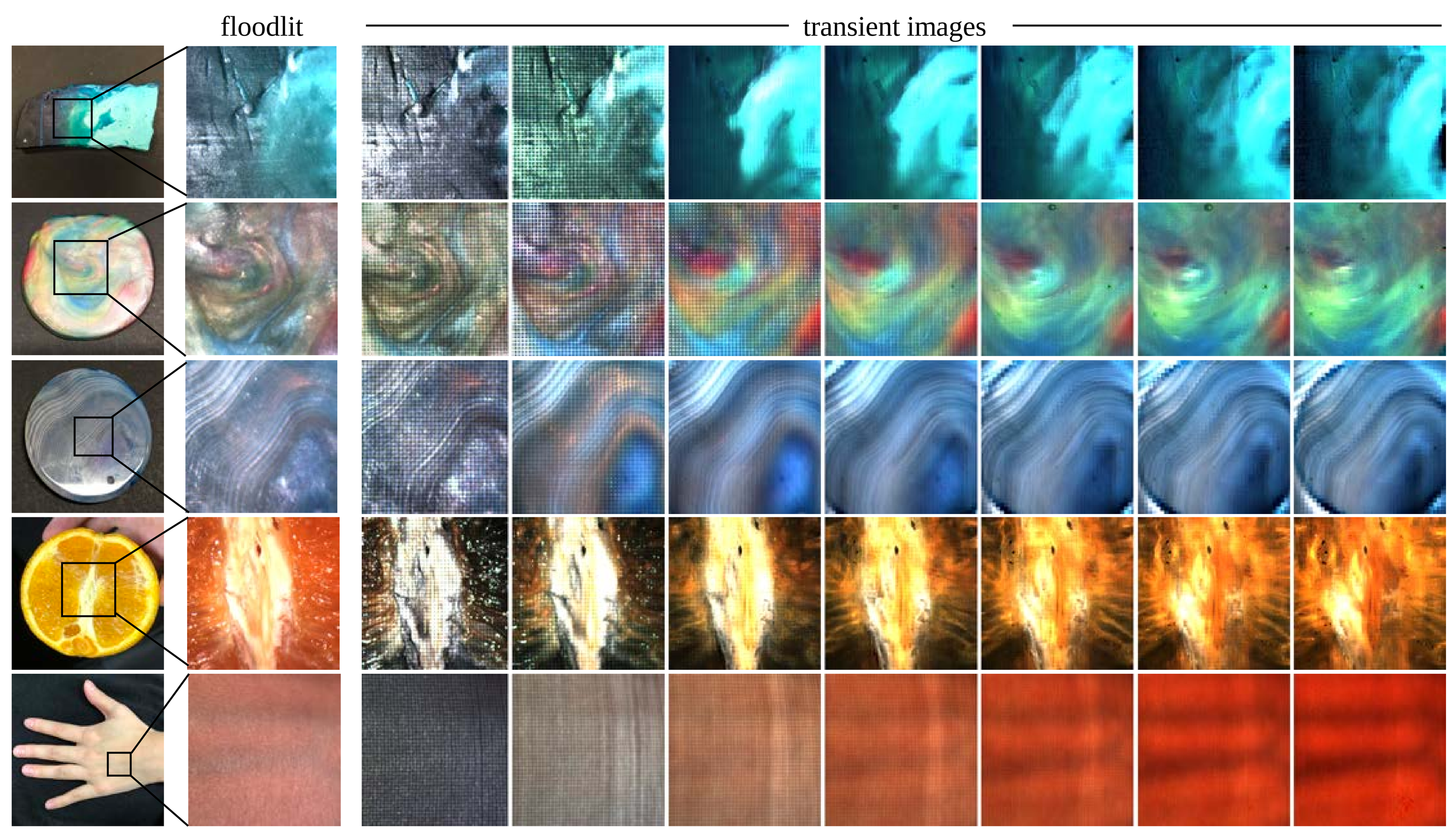
Color from Transient Images

When the surface has subsurface structures that vary across its depth, the bounded path length light in each recovered transient depth directly encodes the accumulated color along its path. We may recover the true color at each corresponding surface depth by taking the difference of the transient images (i.e., the difference of the difference of captured variable ring light images). Note that these colors cannot be directly observed from the outer surface.



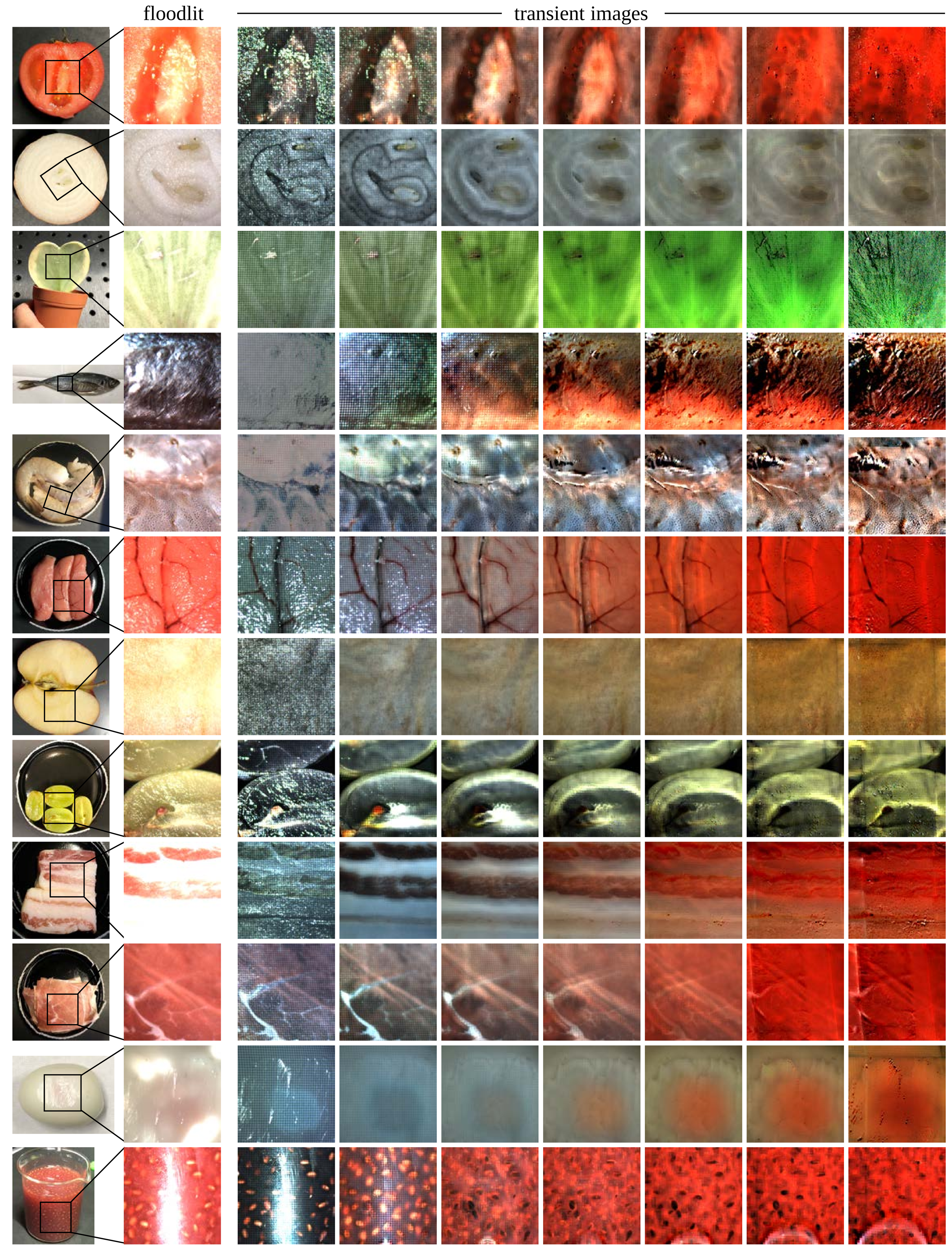
Transients Images of Complex Surfaces

Transient images of complex surfaces reveal the subsurface composition both in its volumetric structure as well as its color variation that are otherwise invisible from the outer surface.



Complex Subsurface Light Transport

Variable ring light imaging may be used to reveal the complex intrinsic surface structures of natural objects.



For high resolution image capture of larger surface regions, we can speed up the imaging with parallel impulse illumination capture.