OLED Outcoupling Benefits and Design

Solid-State Lighting Virtual Workshop

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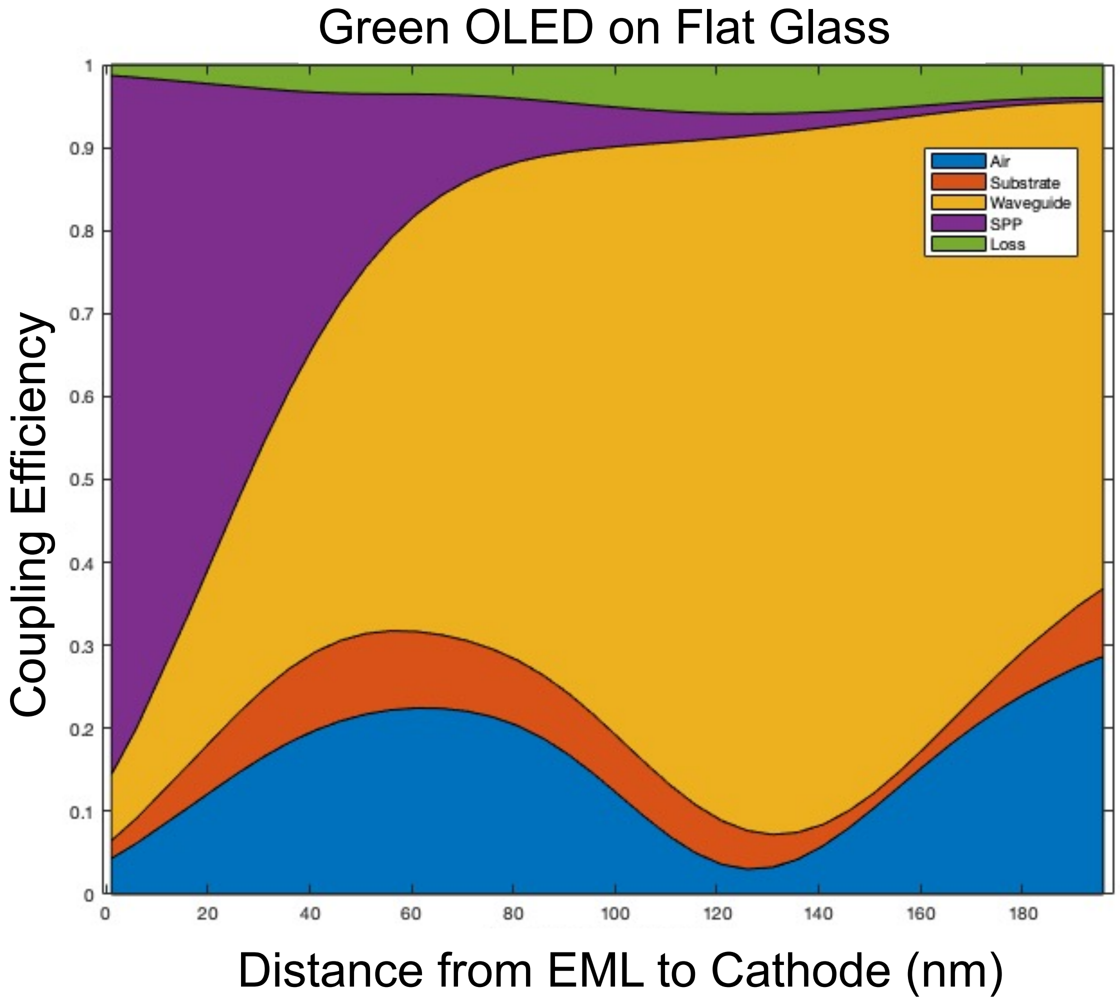
Light extraction in organic light-emitting diodes

- External quantum efficiency (η_{ext}) is the product of internal quantum efficiency (η_{int}) and outcoupling efficiency (η_{oc})

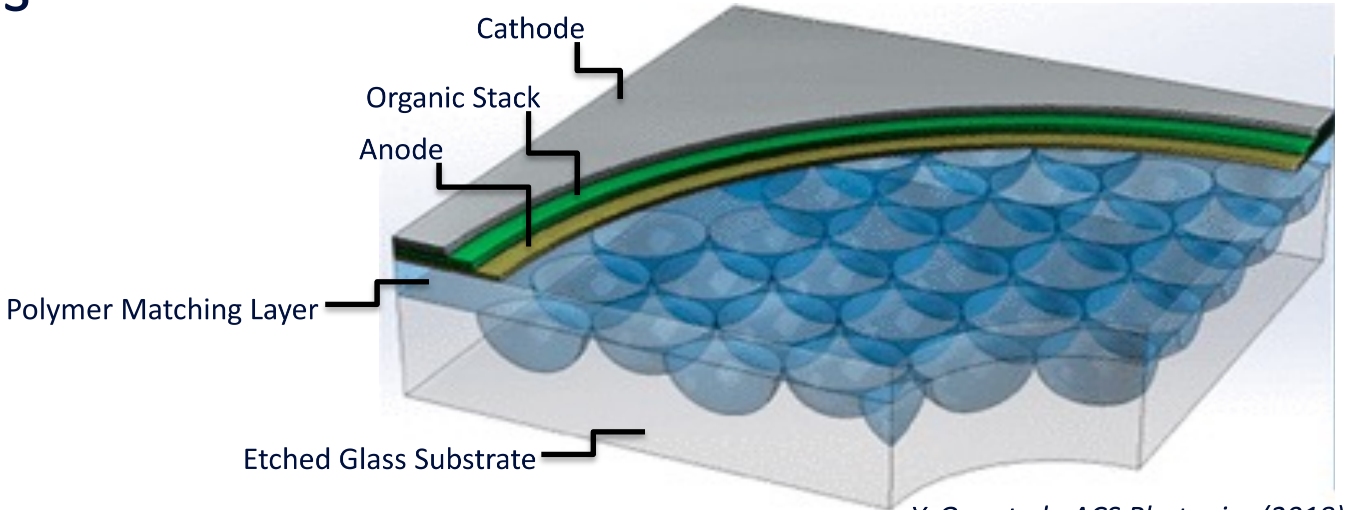
$$\eta_{ext} = \eta_{int}\eta_{oc}$$

- Waveguide modes are the largest source of loss at peak efficiencies



Increasing the coupling efficiency into air modes

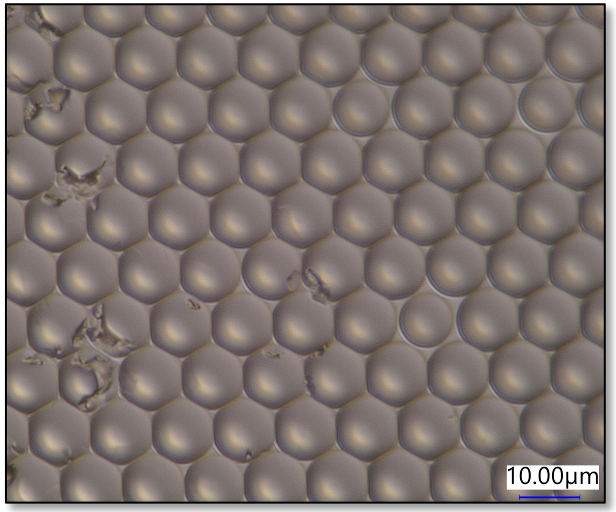
- Internal reflection at substrate/air and organic/substrate interfaces is decreased by:
  1. Decreasing incidence angle
  2. Decreasing index of refraction mismatch
- Sub-electrode microlens arrays (SEMLA) can be used to improve organic/substrate interface

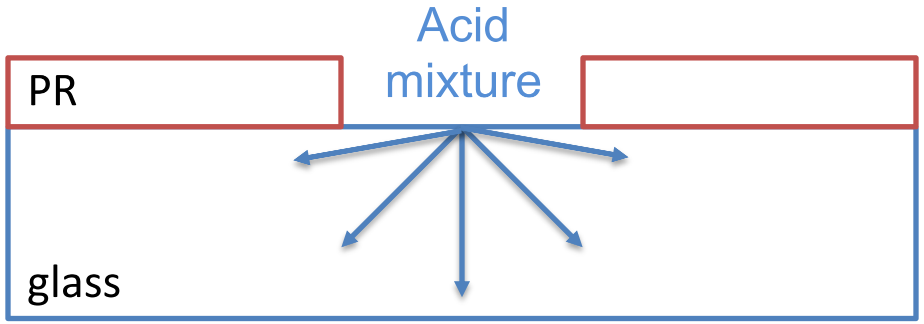


Y. Qu, et al., ACS Photonics (2018)

SEMLA Fabrication

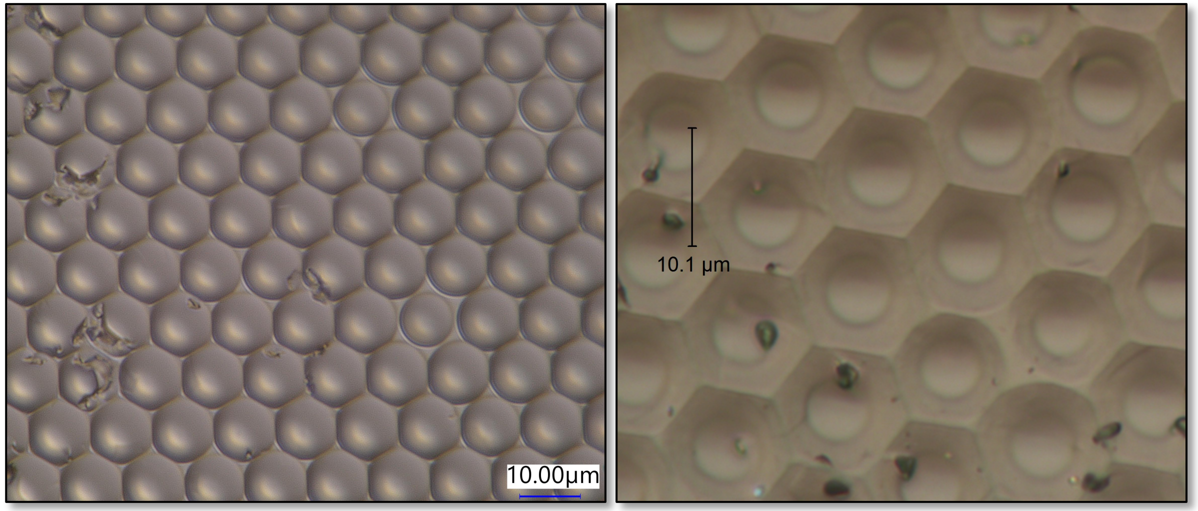
1. Hexagonal close-packed array of 1µm holes with 10µm spacing are patterned in photoresist
2. Substrates are etched in a 1:6 surfactant:buffered HF mixture
3. A high-index polymer is spun to planarize the substrate surface





SEMLA capabilities

- Lens coverage has fill factor = 1
- Can be fabricated in flexible thin glass without decrease in extraction efficiency
  - 200µm Willow® Glass

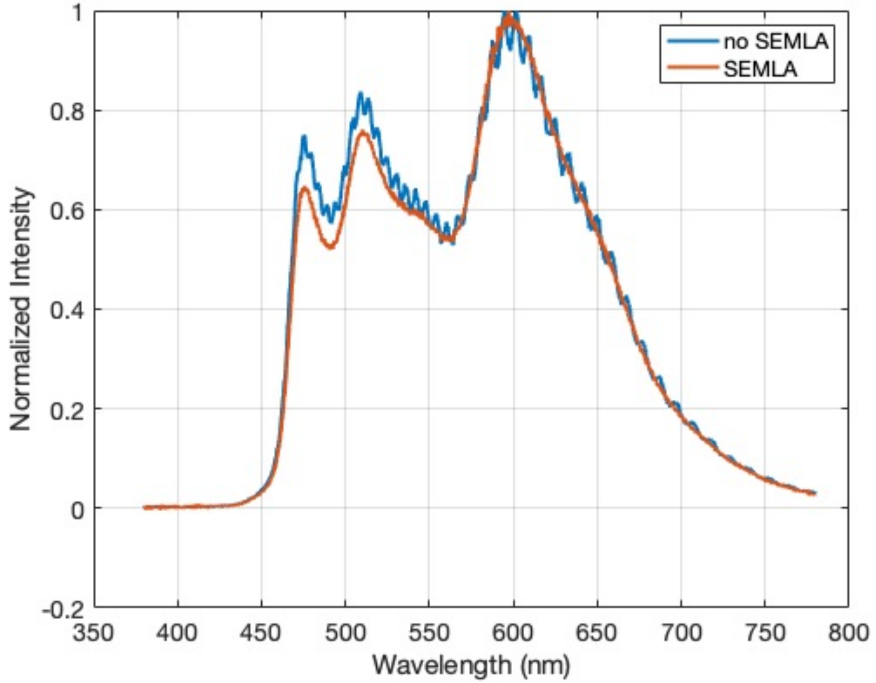


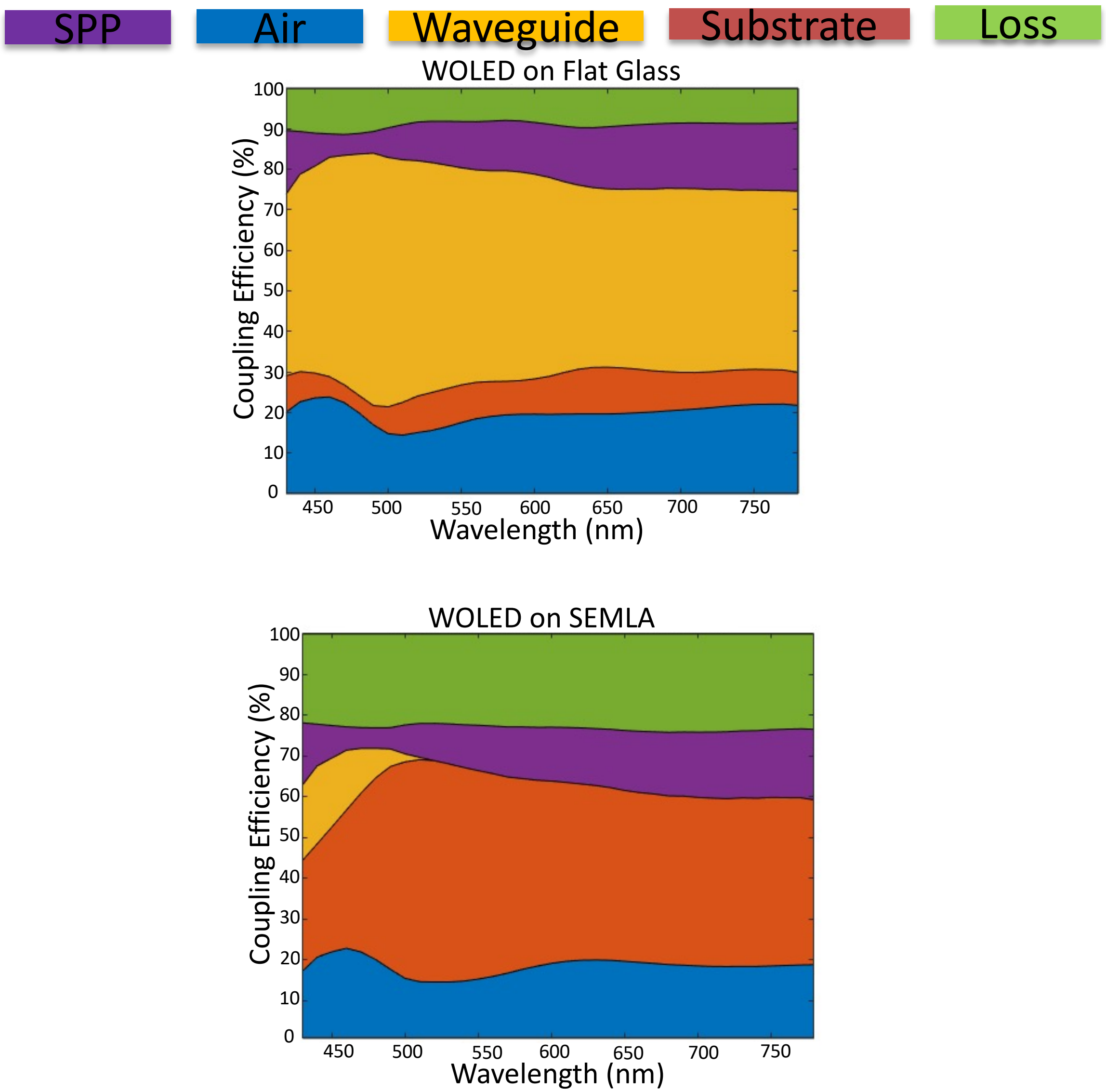
Green OLED Enhancement Factor

	SEMLA	SEMLA + IMF	Reference
Thick glass SEMLA	1.2	2.2	Y Qu, et al. *ACS photonics* 5.6 (2018): 2453-2458.
Thin glass SEMLA	1.2	2.3	[this work]

SEMLA capabilities

- Nearly 100% coupling efficiency from waveguide modes to substrate modes
  - SEMLA alone has an enhancement factor of 1.3 for WOLED
- Spectrum is not changed with SEMLA





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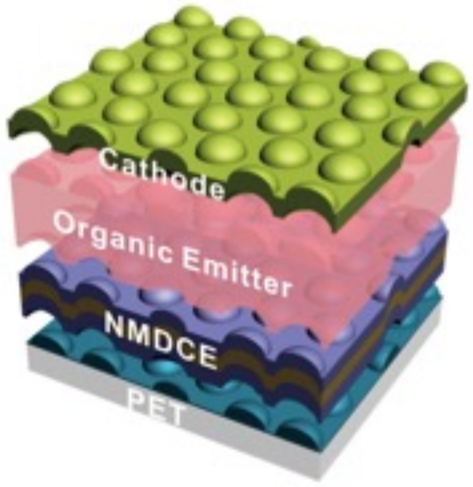
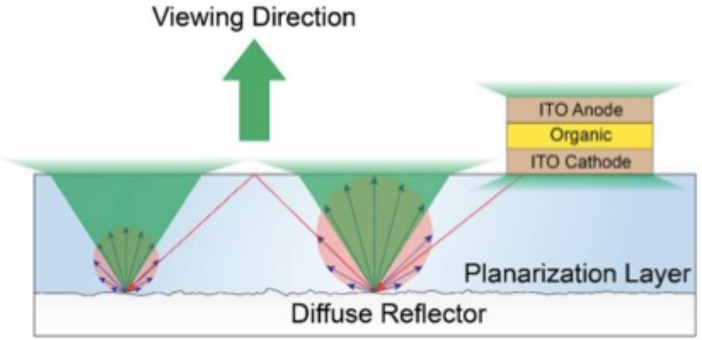
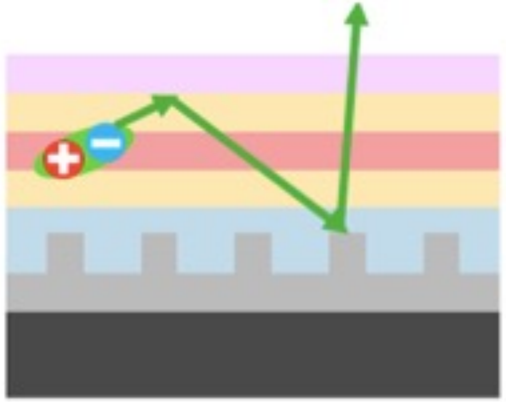
Random Nanostructures[1]



Diffuse Reflector[2]



Scattering Grid[3]



2D Grating[4]

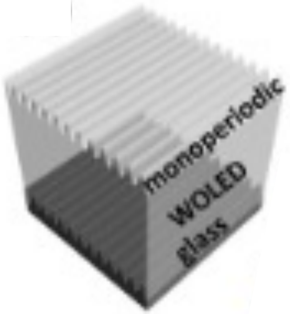


Table modified from A Salehi, X Fu, D-H Shin, and F So, *Adv. Funct. Mater.* **2019**, *29*, 1808803

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Extraction Method	Extracted Modes	Enhancement Factor	Reference
Random Nanostructures	Waveguide (WG) and surface plasmon polariton (SPP)	2.4	[1] L-H Xu, et al. *ACS nano* 10.1 (2016): 1625-1632.
Diffuse Reflector	WG	2.5 (green)	[2] J Kim, et al. *ACS Photonics* 5.8 (2018): 3315-3321.
Scattering Grid	WG	1.5 (green)	[3] Y Qu, et al. *ACS Photonics* 4.2 (2017): 363-368.
2D Grating	WG and SPP	1.48	[4] Y-G Bi, et al. *Advanced Materials* 25.48 (2013): 6969-6974.
SEMLA + substrate outcoupling	WG and substrate	1.7 (MLA), 2.8 (IMF)	[5] Y Qu, et al. *ACS photonics* 5.6 (2018): 2453-2458.

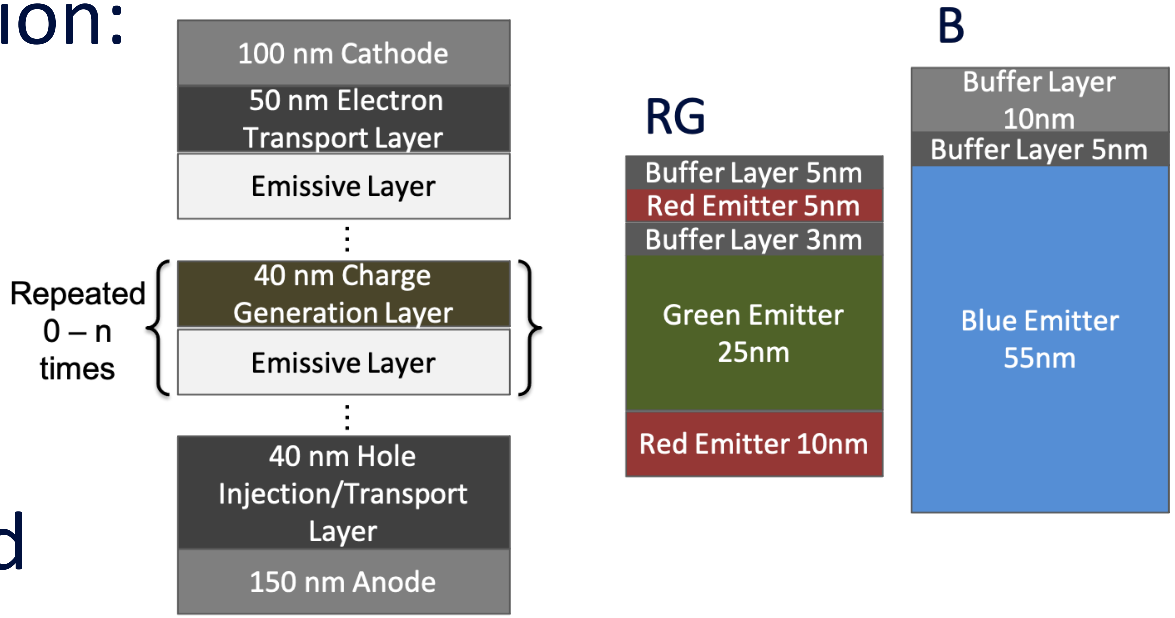
Table modified from A Salehi, X Fu, D-H Shin, and F So, *Adv. Funct. Mater.* **2019**, *29*, 1808803

What’s next for SEMLA?

- Improving substrate mode extraction: not all substrate modes can be coupled out by MLA

  ~20% of photons are trapped in the substrate

- Combining SEMLA with optimized OLED design
  - Deep stacked structures
  - Striped R/G/B design



100 nm Cathode
50 nm Electron Transport Layer
Emissive Layer
⋮
Repeated 0 – n times
40 nm Charge Generation Layer
Emissive Layer
⋮
40 nm Hole Injection/Transport Layer
150 nm Anode

RG
Buffer Layer 5nm
Red Emitter 5nm
Buffer Layer 3nm
Green Emitter 25nm
Red Emitter 10nm

B
Buffer Layer 10nm
Buffer Layer 5nm
Blue Emitter 55nm

EQE	Experiment	Theory	Theory + SEMLA + IMF
3 R/G, 1B	57.7%	59%	252%

C Coburn, C Jeong, and SR Forrest. *ACS Photonics* 5.2 (2018): 630-635.

Acknowledgements

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