Ultrafast Optics

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What are characteristic scales in quantum systems?

classical approach

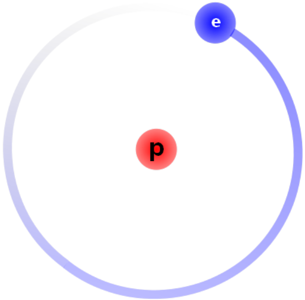
$$v = \sqrt{\frac{2Ry}{m_e}} = \frac{c}{137} = \alpha \cdot c$$

virial-theorem

$$\langle T \rangle = -\frac{1}{2}\langle V \rangle = E_{binding}$$

$$a_0 = 0.53 \cdot 10^{-10} m$$

$$\rightarrow \quad t_{orbit} \approx 150 \cdot 10^{-18} s = 150 as$$



$^{1}_{1}H$

Attosecond-scale means electron motion!

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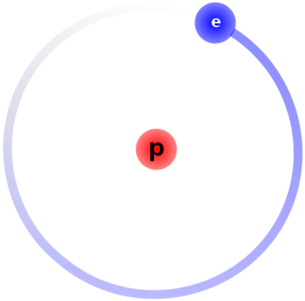

$^{1}_{1}H$

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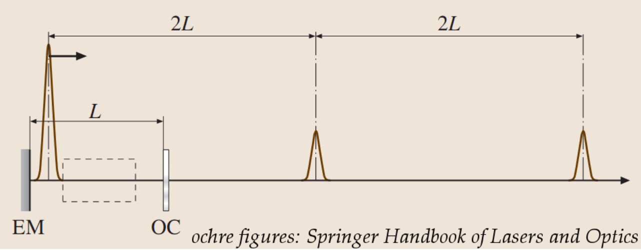
What do we want?

Confine energy in small spatial region!

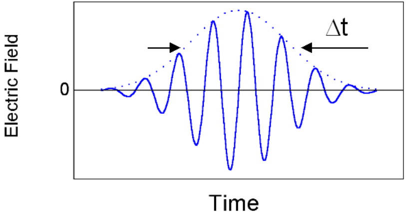


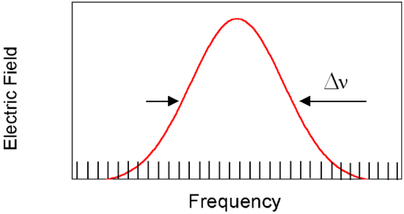
ochre figures: Springer Handbook of Lasers and Optics

Roundtrip:
$$t_{RT} = \frac{2L}{c}$$

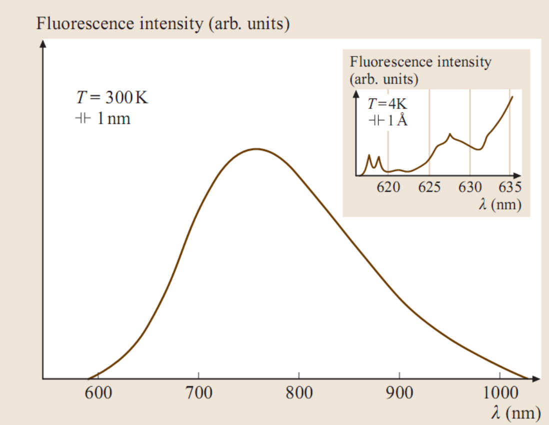
Longitudinal modes:
$$\delta\nu = \frac{c}{2L} = \frac{1}{t_{RT}}$$

time-bandwidth-product:
$$\Delta t \Delta\nu \geq 0.441$$





Ti:Sapphire, $(Ti^{3+} : Al_2O_3)$

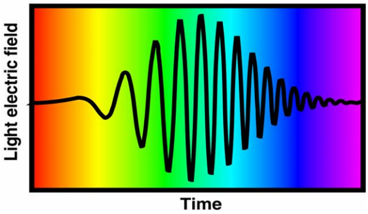


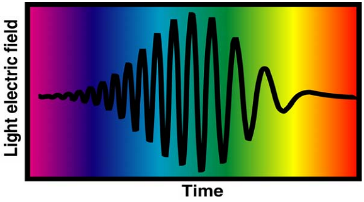
Ti:Sa parameters

$n = 1.76$ $\tau_{fluo} = 3.2\mu s$ $FWHM \approx 200nm$ $\lambda_{max} \approx 790nm$

$\rightarrow$ Issues: temporal & spatial coherence, dispersion

Chirp


Light electric field
Time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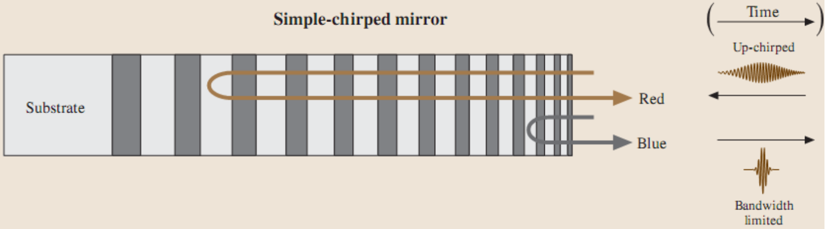
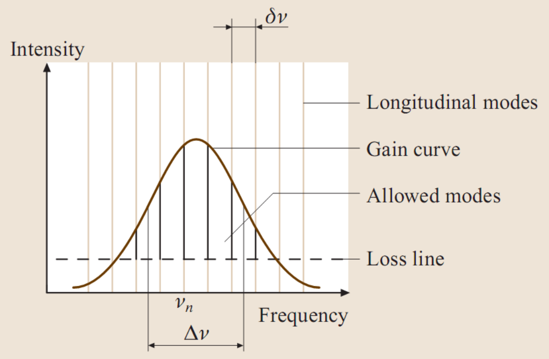

Simple-chirped mirror
Substrate
Red
Blue
Time
Up-chirped
Bandwidth limited

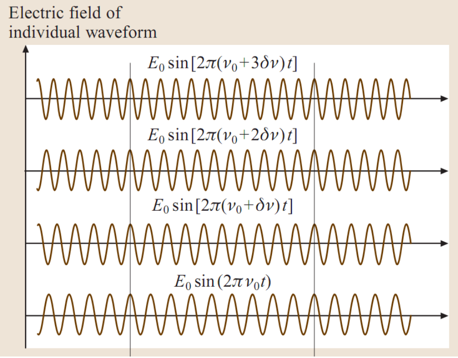
Basic Ideas

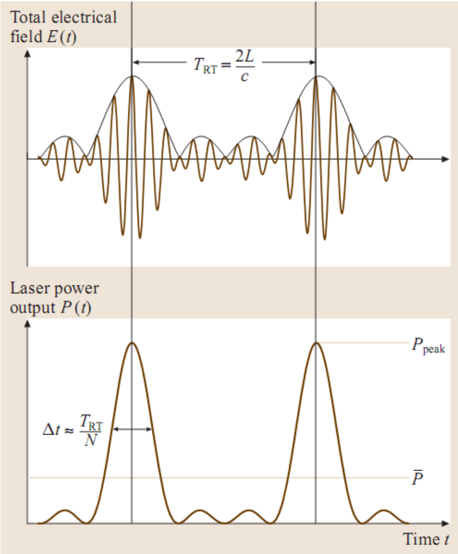


Pulses:

- emitted as trains $t_{RT} = \frac{1}{\delta\nu}$
- peak power $P \propto P_0 \cdot N^2$
- $\Delta t \approx \frac{1}{N\delta\nu} = \frac{1}{\Delta\nu}$
- key parameter: $\phi_n(t)$

Basic Ideas, visualised





Optical Kerr-effect

high intensities $> 10^{14}\,\frac{W}{cm^2}$ $\quad n_{nl} = n_0 + n_2 \cdot I$

$n_2 \approx +(10^{-16} \ldots 10^{-15})\,\frac{cm^2}{W}$

new wave vector $\quad k_{nl} = k(\omega_0) + \frac{\omega_0}{c}\frac{n_2}{A}|g(t)|^2$

time-dependent response $\rightarrow$ Self-Phase-Modulation, SPM

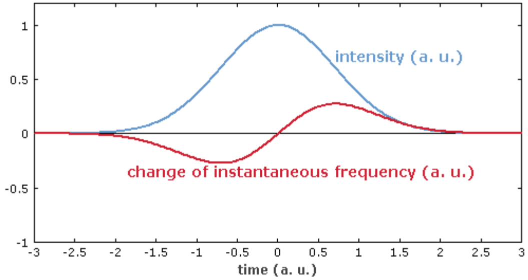


Figure: RP Encyclopedia of Laser Physics and Technology

Self-Amplitude-Modulation, SAM

beam intensity $\propto e^{-r^2}$

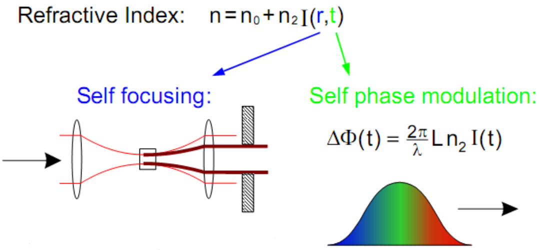


Figure: Ferenc Krausz, Photonics II Lecture

State of affairs

	pulse	rep. rate	crystal	energy/pulse	€
commercial	7 fs	80 MHz	Ti:Sa	$2 \cdot 10^{-9} J$	120.000
commercial	25 fs	3 kHz	Ti:Sa	$7 \cdot 10^{-4} J$	500.000

labs: single cycle regime reached

$\longrightarrow$ as-pulses require different technique

3-Step-Model

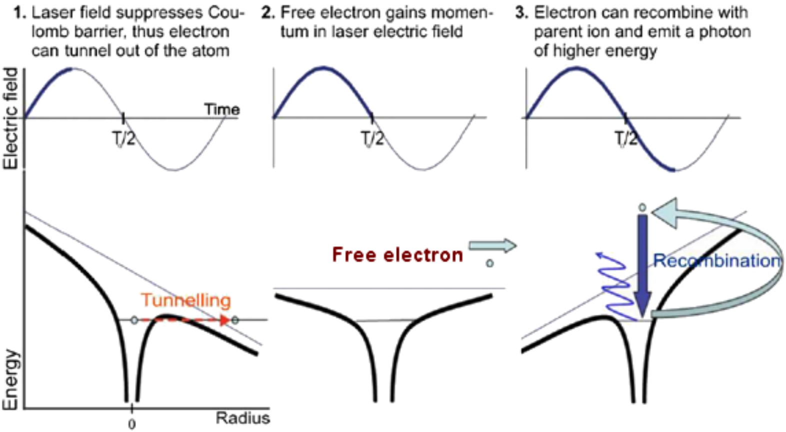


Figure: Corkum, Phys. Rev. Lett. 71, 1994 (1993)

Experimental setup

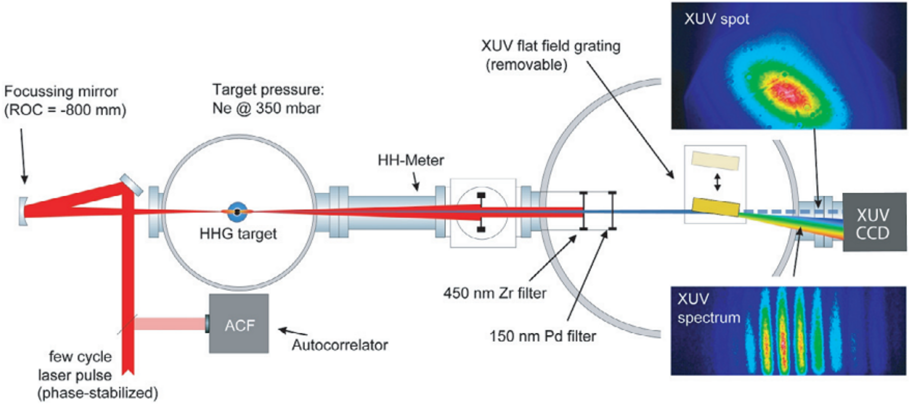


Figure: Cavalieri, New Journal of Physics 9 (2007) 242

HHG, results

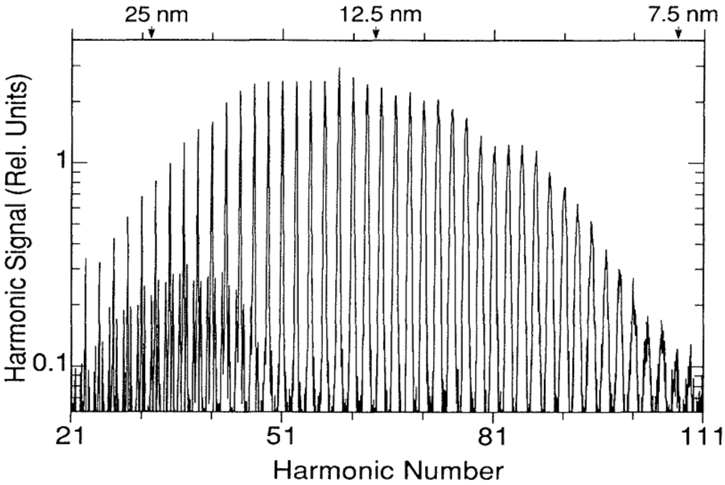


Figure: Macklin, Phys. Rev. Lett. 70, 766 (1993)

3-Step-Model, Remarks

- nonlinear response is not instantaneous
- nonlinear response almost constant at high orders
- maximum electron energy $3.17\ U_P = 3.17\ \frac{E_0^2}{4\omega^2}$
- up to 1000^{th} order $\rightarrow$ keV

XUV pulses reach

E=90eV t=250as $I = 10^{11}\,\frac{W}{cm^2}$

fs-MIR-pulses, setup

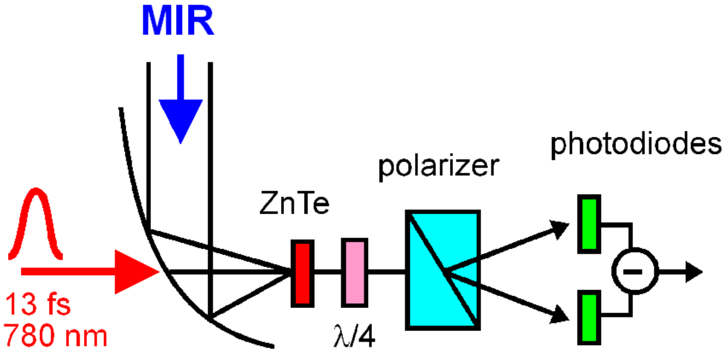
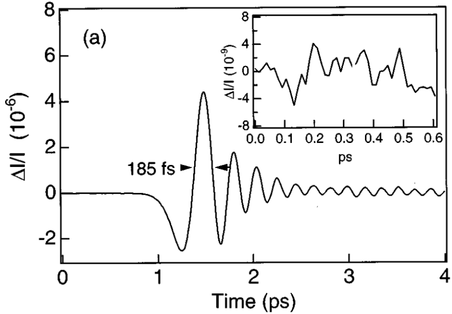


Figure: Q. Wu and X.-C. Zhang, Appl. Phys. Lett. 70 (14), 7 April 1997

$$\frac{I_1 - I_2}{I_1 + I_2} = sin(\Gamma) \qquad \Gamma \propto E_{IR}(t)$$

THz Results



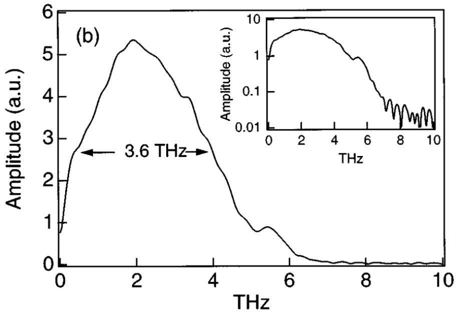
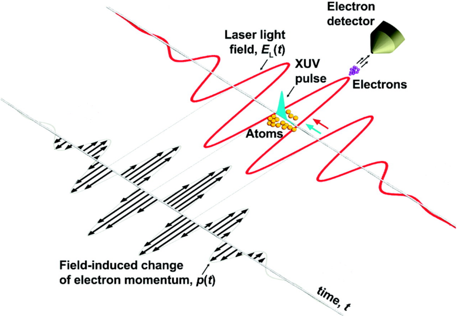
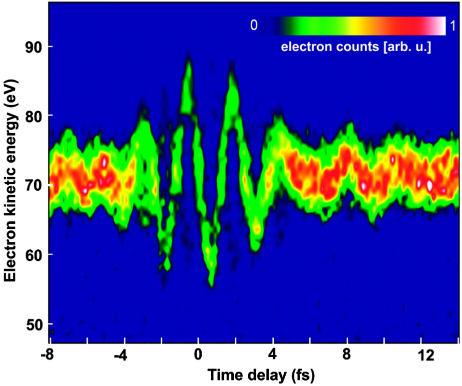


Figure: Q. Wu and X.-C. Zhang, Appl. Phys. Lett. 70 (14), 7 April 1997

Next Step: XUV Probe





Figures: E. Goulielmakis, et al., Science 305 1267 (2004)

sub-10-fs-Methods

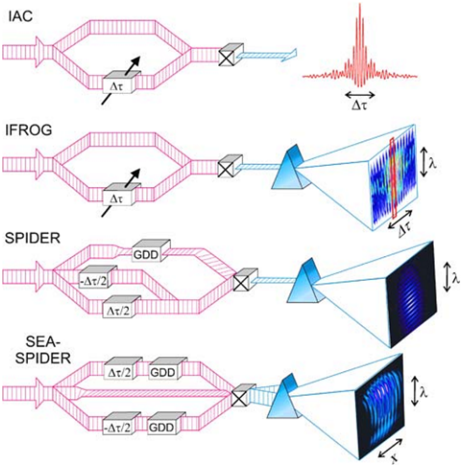


Figure: Stibenz, Steinmeyer et al., Appl. Phys. B 83, 511-519 (2006)

Sea-Spider, schematic

Spatially **E**ncoded **A**rrangement for
Spectral **P**hase **I**nterferometry for **D**irect **E**lectric-field **R**econstruction

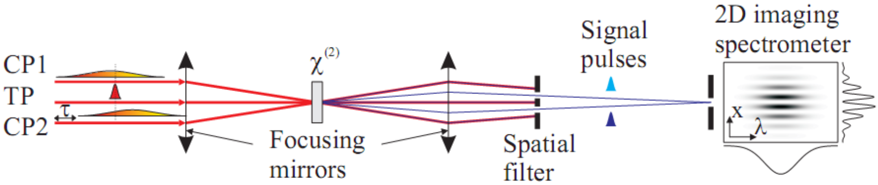


Figure: A. S. Wyatt, I. A. Walmsley, G. Stibenz, and G. Steinmeyer, Opt. Lett. 31, 1914-1916 (2006)

$$S(x,\omega) = |E(x,\omega+\omega_0)|^2 + |E(x,\omega+\omega_0+\Omega)|^2 + 2|E(x,\omega+\omega_0)| \cdot |E(x,\omega+\omega_0+\Omega)| cos(\phi(x,\omega+\omega_0) - \phi(x,\omega+\omega_0+\Omega) + Kx)|$$

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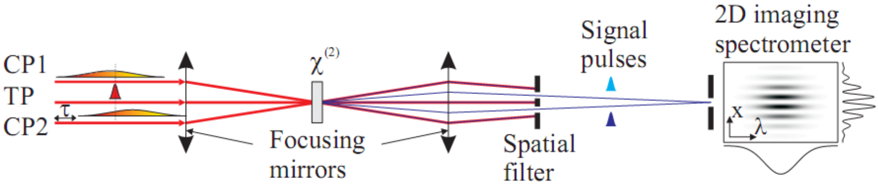

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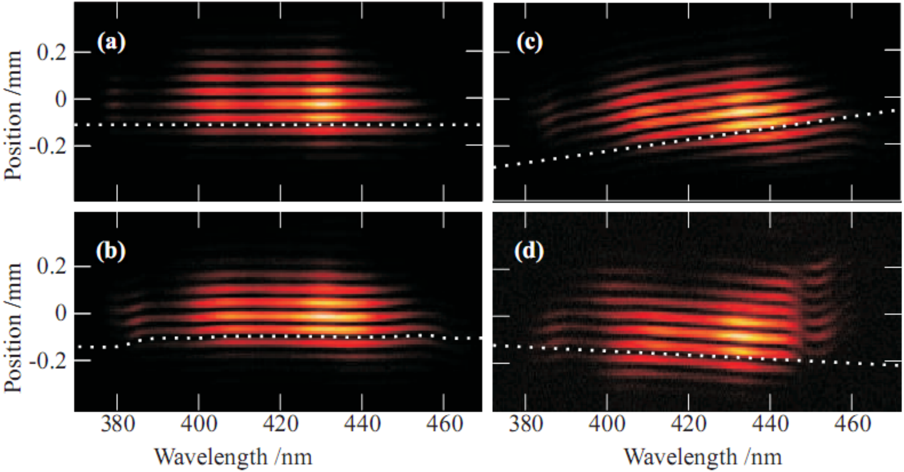
Sea-Spider, results



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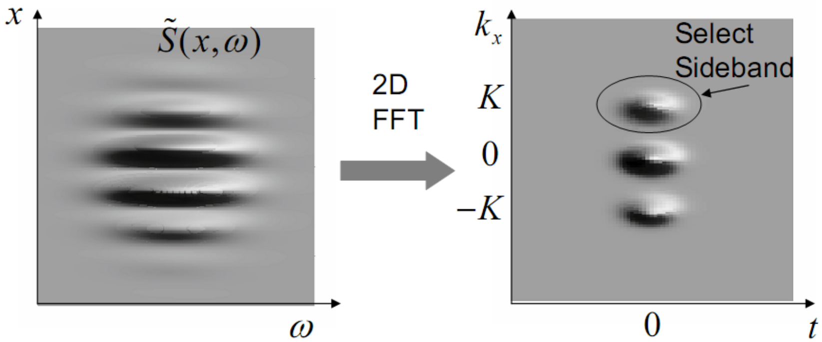
Sea-Spider, processing the results



$$\tilde{S}^{f}(x,\omega)=\left|\tilde{E}(x,\omega+\omega_{\circ})\right|\left|\tilde{E}(x,\omega+\omega_{\circ}+\Omega)\right|$$

$$\times\exp[i\left(\phi(x,\omega+\omega_{o})-\phi(x,\omega+\omega_{o}+\Omega)+Kx\right)]$$

Figure: Ellen M. Kosik, Aleksander S. Radunsky, Ian A. Walmsley, and Christophe Dorrer, Opt. Lett., 30 (3), 326-328, (2005)

Sea-Spider, enjoying the results

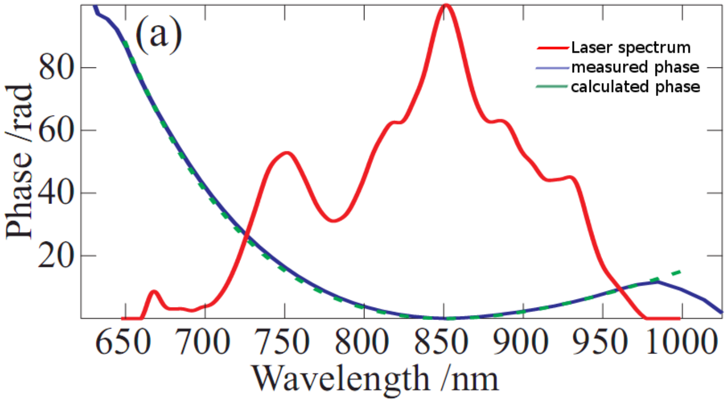


Figure: A. S. Wyatt, I. A. Walmsley, G. Stibenz, and G. Steinmeyer, Opt. Lett. 31, 1914-1916 (2006))

Applications & Conclusions

Applications

- communications ($1,4\mu m$ gap)
- THz-Imaging & -Sampling (low absorption)
- medical & biological microscopy (increased resolution)
- structuring & cutting (no heat diffusion)
- ultrafast metrology (exiting and probing with short pulses, dynamics)
- control of chemical reactions (valence electrons, shaped pulses)

Conclusion

Ultrafast optics breaks new ground in

- high-field science
- frequency and time metrology
- industrial, medical and biological technologies

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