Multichannel Superposition of Grafted Perfect Vortex Beams

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1. Introduction

An optical vortex (OV) beam has a helical phase profile described by exp (i\(\varphi l\)), where \(l\) is the topological charge (TC) and \(\varphi\) is the azimuthal angle.\(^1\) The OV beam can be converted into a doughnut-shaped ring with the transverse component of Poynting vectors. Owing to the azimuthally dependent phase, an OV beam possesses an orbital angular momentum (OAM), which plays a vital role in various applications such as optical communications,\(^2\) optical imaging,\(^3\) particle manipulation,\(^4\) and OAM microlasers.\(^5\) The diameter of the light ring is strongly dependent on the TC, hindering the coupling of multiple OVs in an optical fibre.\(^6\) To solve this problem, Ostrosky et al. proposed the concept of the perfect optical vortex (POV),\(^7\) which exhibits a constant intensity profile and a radius irrespective of the TC.\(^8\) For conventional OV and POV beams, the OAM distribution on the ring is uniform. This uniformity is not suitable for applications where versatile OAM distributions are needed, e.g., multiparticle trapping and manipulation. Therefore, noncanonical optical vortices are proposed to tackle these challenges. Examples include spiral OAM distributions,\(^8\) nonuniform hollow circular OAM distributions,\(^9\) and structured OAM distributions.\(^10\) However, these OAM distributions are strongly dependent on the intensity and the local OAM modulation is impossible. A grafted optical vortex, which is generated through grafting two or more spiral phase profiles of optical vortex beams, has a controllable OAM distribution and constant intensity.\(^11\) Recently, grafted perfect vortex beams (GPVBs) have attracted much attention due to their unique optical properties (e.g., versatile OAM distributions) and potential applications (e.g., more options for particle manipulation). However, the generation and manipulation of GPVBs are more challenging and complicated due to the involvement of an additional phase profile of a lens and that of an axicon. The optical setups currently being used for generating GPVBs are complex, requiring numerous optical components, including spatial light modulators, lenses, pinhole filters, polarizers, and dichroic mirrors,\(^12\) which result in large space requirement and high cost. These optical systems are impractical for many applications, and hence there is a pressing requirement for a compact, simple, and efficient approach to generating and manipulating GPVBs.

Optical metasurfaces have been used in a range of ultrathin optical devices, including metalenses,\(^14-16\) polarization detectors,\(^17-19\) holograms,\(^20-23\) and high-resolution imaging.\(^24,27\)
Metasurfaces allow the unprecedented manipulation in phase, amplitude, and polarization, opening up exciting opportunities for the generation and manipulation of various types of OV beams,\cite{28-30} including POVs,\cite{31,32} ring vortex beams,\cite{20,33,34} and vortex beam holography.\cite{22,35} For example, a single-layer spin dependent metasurface is employed to realize various states of POVs on the hybrid-order Poincaré sphere.\cite{36,37} Recently, numerous attempts have been made to demonstrate multidimensional manipulation of wave fields.\cite{38} Deng et al. introduced a non-orthogonal arbitrary polarization multiplexing approach using vectorial compound based metasurfaces for high fidelity grayscale images.\cite{39} In comparison to the previous approaches that were only limited to circular and linear polarization states, a perfect dichroism of greater than 90% was realized for arbitrary polarization states.\cite{40} To tackle the fundamental and technical challenges in more conventional optics, we propose and experimentally demonstrate a metasurface based approach to generating and manipulating GPVBs in multiple channels. To the best of our knowledge, this is the first time that a single metasurface has been used to generate various GPVBs and realize the coaxial superpositions of these beams in different channels, without relying on the complex conventional optical setup. The uniqueness of this method is that the superimposed GPVBs have nonuniform OAM and asymmetric singularity distributions in different channels, which can be modulated by introducing an initial phase difference in the metasurface design. The proposed metasurface approach can facilitate system integration and device miniaturization and has strong potential for novel applications that may not be possible with conventional optics.

2. Design Methodology

Figure 1 shows the schematic of the proposed multichannel bilayer geometric metasurface device for the generation and manipulation of GPVBs. Upon the illumination of a right circularly polarized (RCP) light beam, various superpositions of GPVBs are realized in four different channels. The superposition of GPVBs in each channel features nonuniform OAM and asymmetric singularity distributions. The numbers of singularities in the upper and lower half of the composite beam can be separately engineered with different combinations of TCs. Moreover, the singularity distribution can be further modulated by using an initial phase in the metasurface design. This initial phase is added to one of the GPVB to generate the desired phase difference (see Section 3 for details). The geometric metasurface consists of resist nanoslits with spatially varying orientations sitting on the glass substrate, followed by the deposition of a 40 nm-thick gold film.

To realize such a device, we start from the POV generation. A typical POV beam can be obtained through the Fourier transformation of a Bessel–Gaussian (BG) beam, which can be achieved with a Gaussian beam passing through a spiral phase plate, an axicon, and a lens. Theoretically, the complex amplitude of transformed BG is governed by:\cite{8}
Figure 2. Superposition of POV beams. a) POV with radius $R_1$ and $l_1 = +3$. Two peaks are observed in the intensity profile along a horizontal line that passes through the centre of the light ring. b) POV with radius $R_2$ and $l_2 = -3$. c) Intensity distribution of superimposed POV beams. The dashed circle “$R_o$” indicates the radius of the middle circle between the two concentric circles shown in (a) and (b), respectively. The solid white and green curves indicate the normalized 1D intensity profiles at the focal plane.

$$E(r, \psi) = G \exp(i \psi) \exp\left(-\frac{(r-R)^2}{\alpha^2}\right)$$  \hspace{1cm} (1)

where $(r, \psi)$ are the polar coordinates, $G$ is a constant, and $R$ is the radius of the POV ring. $\alpha = \frac{2f}{k \omega}$ is the beam waist at the focal plane, where $f$ is the focal length, $k$ is the wavenumber, and $\omega$ is the beam waist of an incident Gaussian beam. Consider the superposition of two POVs (shown in Figure 2a,b) with TCs $l_1 = +3$ and $l_2 = -1$, whose corresponding radii are $R_1$ and $R_2$, respectively. The mathematical relation can be expressed as:

$$E_1(r, \psi) = E_1(r, \psi) + E_2(r, \psi)$$  \hspace{1cm} (2)

where

$$E_1(r, \psi) = G \exp(i \psi) \exp\left(-\frac{(r-R_1)^2}{\alpha_1^2}\right)$$  \hspace{1cm} (3)

and

$$E_2(r, \psi) = G \exp(i \psi) \exp\left(-\frac{(r-R_2)^2}{\alpha_2^2}\right)$$  \hspace{1cm} (4)

The interference occurs in the region where two POVs meet with each other. We can clearly see the dark holes in the interference patterns (shown in Figure 2c). Each dark hole corresponds to a singularity. The complex amplitude of the resultant beam can be simplified as

$$E_1(R_2, \psi) = G \exp\left[-\frac{(R_2-R_1)^2}{\alpha_2^2}\right] \exp\left[i \frac{(l_1+l_2)}{2} \psi\right] \cos\left[i \frac{(l_2-l_1)}{2} \psi\right]$$  \hspace{1cm} (5)

The detailed derivation process based on Equation (2) is provided in Section S1, Supporting Information. It can be inferred from Equation (5) that the total number of singularities is $L = |l_2 - l_1| = |-3 - 3| = 6$.

The idea of a grafted perfect optical vortex beam is inspired by the plant grafting, i.e., the joining together of the tissues of two plant parts. One can place a portion of one plant (scion) on a stem, branch, or root of another (rootstock) in such a way that a new plant will be formed (Figure 3a). Similar to the plant grafting, two or more spiral phase profiles can be grafted together from a bespoke metasurface design. For example, a grafted optical vortex beam can be generated with the upper half of a vortex beam with TC $l_1 = +3$ as a scion and the lower half with $l_2 = -1$ as a rootstock (see Section S3, Supporting Information). Interestingly, it can be seen that positive and negative TCs can be combined in the same light beam. GPVBs are TC independent on the intensity ring. The complex amplitude of GPVB in the focal plane can be written as:

$$E_{GPVB}(r, \psi) = G \exp\left[\frac{\sum_{n=1}^{\infty} N_1} {2 \pi} \left[\frac{N_1}{2\pi} - N + 1 + n\right] \psi \exp\left[-\frac{(r-R)^2}{\alpha^2}\right]\right]$$  \hspace{1cm} (6)

where $N_1$, $l_1$, and $\psi$ are the number of involved vortex beams, TCs, and the azimuthal angle, respectively.

To realize the GPVB superposition, bilayer metasurfaces are used. In comparison with a single layer of plasmonic metasurface consisting of gold nanorods, a bilayer plasmonic metasurface can effectively suppress the nonconverted part and alleviates the requirement for a lift-off process during the fabrication. Detailed analysis is available in Section S2, Supporting Information. The bilayer metasurface can simultaneously realize the phase profiles of a GVB, an axicon, and a Fourier transformation lens upon the illumination of the RCP light. The complex phase profile of two superimposed GPVBs ($\phi_{GS}$) is governed by the following equation:

$$\phi_{GS}(x, y) = \phi_{GPVB1} + \phi_{GPVB2}$$  \hspace{1cm} (7)

where

$$\phi_{GPVB1} = \text{arg}[E_1 \exp[i(\phi_{\text{axicon}} + \phi_{\text{GVB1}, l_1} + \phi_{\text{axicon}, d_1})]]$$

and

$$\phi_{GPVB2} = \text{arg}[E_2 \exp[i(\phi_{\text{axicon}} + \phi_{\text{GVB2}, l_2} + \phi_{\text{axicon}, d_2})]]$$

Here, $E_1$ and $E_2$ are the amplitudes of two GPVBs, $\phi_{\text{axicon}} = -k(\sqrt{x^2 + y^2 + f^2} - |f|)$ is the phase profile of a lens, $k = \frac{2\pi}{\lambda}$ is the wavenumber, $f = 150 \mu m$ is the focal length, and $\lambda = 650 \text{ nm}$ is the operating wavelength. $\phi_{\text{axicon}} = -\frac{2\pi \sqrt{x^2 + y^2}}{d}$ is the phase profile for the axicon, where $d$ is the axicon period to control the radius of the generated intensity ring. We choose $d_1 = 2.9 \mu m$ and $d_2 = 3.29 \mu m$ for $\Phi_{\text{axicon1}}$ and $\Phi_{\text{axicon2}}$, respectively. The calculation of $\Phi_{\text{GVB}}$ is based on Equation S15 in Section S3, Supporting Information. The calculated phase profiles for the three superpositions of GPVBs with various combinations of TCs (left: $l_{11} = +3$, $l_{12} = -1$ and $l_{21} = -3$, $l_{22} = +1$, middle: $l_{11} = +3$, $l_{12} = -1$ and $l_{21} = -3$, $l_{22} = +1$, right: $l_{11} = +3$, $l_{12} = -1$ and $l_{21} = -3$, $l_{22} = +1$, respectively).
Figure 3. GPVB generation and superposition. a) Schematic of GVB generation in comparison with plant grafting. b) Desirable phase profiles for different superpositions of GPVBs with various combinations of TCs. Left: $l_{a1} = +3$, $l_{a2} = -1$ and $l_{b1} = -3$, $l_{b2} = +1$, Middle: $l_{a1} = -2$, $l_{a2} = -4$ and $l_{b1} = +2$, $l_{b2} = +4$, Right: $l_{a1} = +5$, $l_{a2} = -1$, and $l_{b1} = -5$, $l_{b2} = +1$. c) SEM images of the fabricated bilayer metasurfaces corresponding to the design in (b).

$la_{1} = -2$, $la_{2} = -4$ and $lb_{1} = +2$, $lb_{2} = +4$, right: $la_{1} = +5$, $la_{2} = -1$ and $lb_{1} = -5$, $lb_{2} = +1$ are shown in Figure 3b. The designed metasurface devices are realized using the geometric bilayer metasurfaces, which can produce spatial Pancharatnam–Berry phase profiles associated with the circular polarization states of the incident light beam. The desired phase profiles are realized by controlling the rotation angles of the individual nanorods.[15,18] The scanning electron microscopy (SEM) images of the three fabricated samples are illustrated in Figure 3c. The nano fabrication details are provided in the Experimental section.

3. Results

Figure 4a is the schematic of the experimental setup used to characterize the fabricated samples. A supercontinuum laser (NKT-SuperK EXTREME) with tunable wavelengths is used as the light source. The wavelength in our experiment is fixed at 650 nm. The circular polarization is generated using a linear polarizer (LP) and a quarter-wave plate (QWP). An objective with a magnification of 50 × is used to collect the light on the transmission side and a charge-coupled device (CCD) camera is utilized for visualization after the transmitted light passes through another pair of QWP and LP. Although the nonconverted part can be suppressed, it cannot be completely removed. This leads to a slight background noise in the measured intensity images, which can be further improved with another pair of QWP and LP. The experimental results without and with another pair of QWP and LP are provided in Section S6, Supporting Information (Figure S8 (Supporting Information)).

Figure 4b shows the simulated and measured intensity distributions of the superpositions of GPVBs when the metasurfaces are illuminated by an RCP light beam at normal incidence. All the simulated intensity distributions are acquired through the Fresnel–Kirchhoff diffraction integral.[35] The measured patterns are in good agreement with the simulation results, which confirms the superposition of GPVBs. The number of singularities in the superposed beam can be calculated through the relation $L = \frac{1}{2}(L_{1} + L_{2})$ = $\frac{1}{2}(l_{a1} - l_{b1}) + \frac{1}{2}(l_{a2} - l_{b2})$, where $L_{1}$ and $L_{2}$ represent the number of singularities in the upper half and that in the lower half, respectively. Unlike the superposition of POV beams (Figure 1c), the superposition of GPVBs shows asymmetric singularity distributions in both halves. The
conversion efficiency and operation bandwidth are discussed in Section S2, Supporting Information. The experimental results for the proposed design at different wavelengths are also provided in Figure S10 (Supporting Information).

To quantitatively evaluate the GPVBs, we integrate the far field intensity (simulation and experiment) over a ring with respect to the azimuthal angle ranging from 0° to 360° (Figure 4b,c) shows corresponding normalized intensity distribution. The simulated and experimental results are shown in black and red solid curves, respectively. The upper and lower halves of the superimposed GPVBs are represented in the intervals 0° to 180° and 180° to 360°, respectively. The dips (“1,” “2,” “3,” and “4”) in the curves (left column of Figure 4c) indicate the singularity positions of the composite light beam. The separation between two adjacent dips gives the angle between two singularities. The same procedure is used to calculate the intensity distributions shown in middle and right column of Figures 4c. The slight difference between experiment and simulation is mainly due to the fabrication tolerances and imperfection of the optical setup (e.g., inaccurate alignment). Nevertheless, the equal number of dips (in both simulation and experiment) confirm the existence of singularities in the superimposed beam. The topological charges for the singularities in the superimposed beam are discussed in Section S9, Supporting Information. Moreover, the uneven singularity distributions give us more degrees of freedom to engineer the singularity distribution in the superposition of GPVBs, which can be used to trap and manipulate multiple particles.

In the following, we analyze the effect of the initial phase on the modulation of superposed GPVBs. An additional phase \( \Phi \) is added to produce the phase difference between the two GPVBs. Therefore, the complex amplitude can be expressed as:

\[
E_T(r, \psi) = E_{GPVB1}(r, \psi)e^{i\Phi} + E_{GPVB2}(r, \psi)
\]

where \( \Phi \) is the initial phase. The rotation angles of the superimposed beam are theoretically calculated by the expressions
\[ \theta_1 = \frac{\phi}{|l_{11} - l_{12}|} \quad \text{(for upper half)} \quad \theta_2 = \frac{\phi}{|l_{21} - l_{22}|} \quad \text{(for lower half)}, \]

which indicate that two rotation angles can be modulated separately. Figure 5a shows the simulated and experimental results of the superposition of GPVBs (with \( l_{11} = +4 \), \( l_{12} = +2 \) and \( l_{21} = -4 \), \( l_{22} = -2 \)) with \( \Phi \) ranging from 0 to \( 2\pi \) with the interval of \( \pi/2 \) (the corresponding phase profiles and SEM images are provided in Section S4, Supporting Information). The white solid line indicates the central positions of two original singularities, which are located on the two different halves of the superimposed beam. Blue and green dashed lines show the new central positions of the two singularities in the upper and lower half, respectively. As \( \Phi \) increases, the phase difference increases, which results in the rotation of singularities in the clockwise direction. Furthermore, the rotation angles of the singularities in the upper half and lower half of superimposed beam are different. The difference can be clearly observed with the increase of initial phase, which is further elaborated through Figure 5b. Here, the theoretically calculated, simulated, and experimentally acquired rotation angles are plotted against the initial phase. When \( \Phi \) is increased to \( 2\pi \), \( \theta_1 \) is rotated by 0.78 radians while \( \theta_2 \) is 1.57 radians. Considering the given TCs, the speed of rotation in the lower half is approximately double compared to that in the upper half. Besides, the direction of rotation can be changed by altering the sign of \( \Phi \). In this way, the position of each singularity is precisely controlled by controlling the initial phase. This unique property of GPVB is useful to accelerate and accurately position the trapped micro/nanoparticles.

The proposed methodology is further used to realize the superposition of GPVBs in multiple channels. The desired phase profile to perform such a task in four channels is given by:

\[
\varphi_{\text{MUS-C4}}(x, y) = \arg \sum_{m=1}^{4} E_1 \exp \left[ i (\varphi_{\text{murn}} + \varphi_{\text{CVB1m}} + \varphi_{\text{cxwm}} + \varphi_{\text{nm}}) \right] + E_2 \exp \left[ i (\varphi_{\text{murn}} + \varphi_{\text{CVB2m}} + \varphi_{\text{cxwm}}) \right]
\]

where

\[ \varphi_{\text{murn}} = -k(\sqrt{x^2 - x_m^2} + \sqrt{y^2 - y_m^2})^2 + f^2 - \sqrt{f^2 + x_m^2 + y_m^2} \]

\( x_m \) and \( y_m \) are the transverse coordinates for the \( m \)th channel, where \( m = 1, 2, 3, \) and \( 4 \) (integer). \( \Phi_m \) is the initial phase for \( m \)th channel. A single metasurface can simultaneously impart the initial phase with an interval of \( \pi/2 \). Consequently, each channel can realize the superposition of GPVBs with a different singularity distribution. The rotation angles of the singularities in the upper half are different from those in the lower half. The corresponding phase profile and SEM images of the fabricated metasurface are given in Section S5, Supporting Information. Figure 6a provides the simulated (left) and experimental (right) intensity distribution of multi-channel GPVB superpositions. The simulation results without and with the consideration of complex amplitude modulation are assessed in Section S7, Supporting Information. Although the results look slightly better when the complex amplitude information is considered, the nano-fabrication of such design is quite challenging due to the involvement of nano-pillars with distinct feature sizes. In comparison with the singularity distribution in the superimposed beam with an initial phase \( \Phi_m = 0 \), the positions of singularities in the upper half and the lower half of beam are rotated by two angles when \( \Phi_m \neq 0 \). The calculated, simulated, and measured rotation angles for all four channels are demonstrated by a bar graph in Figure 6b. These results are in good agreement. In addition, we also demonstrate the multichannel metasurface with different combinations of TCs. Figure 6c shows the corresponding calculated (left) and measured (right) results, respectively. The asymmetric singularity distribution in each channel is observed. The total number of singularities (L) in channel-1, 2, 3, and 4 are 4 (3 in upper and 1 in lower half), 6 (4 in upper half and 2 in lower half), 6 (5 in upper and 1 in lower half), and 5 (3 in the upper half and 2 in the lower half), respectively.

4. Discussion

In addition to the fundamental properties of light (e.g., amplitude, phase, polarization), the OVs have been used as an
alternative degree of freedom for multiplexing modulation, increasing the capacity of optical communications. Unlike conventional OVs, GPVBs can be formed through grafting two or more spiral phase profiles of the OVs, providing more degrees of freedom, which can further increase the information capacity. For example, different combinations of TCs with positive and negative signs can be integrated in the same light beam. The current method to generate GPVBs is limited by large space requirements and high cost of the optical setup, hindering the practical applications and further investigation of GPVBs. We demonstrate a compact metasurface platform to realize the GPVBs superposition in multiple channels, offering numerous promising applications related to OVs with significant possibilities that require further exploration. This work has subjugated technical challenges in the currently used optical system, including optical element misalignment, phase aberration, and bulky experimental setup. The superpositions of grafted OAM modes in multiple channels are easily realized with a single metasurface and without additional optical elements. The number of singularities in the upper half and lower half of superimposed beam can be separately engineered. Furthermore, the positions of singularities in the composite beam in each channel can be rotated by controlling the initial phase, allowing a simple repositioning of the singularities.

As a proof of concept, we use plasmonic bilayer metasurfaces with a lower conversion efficiency, which can be dramatically increased with dielectric metasurfaces. 2D transition metal dichalcogenides (TMDs) based designs can offer ultra-thin meta-optics with thickness down to several atomic layers,[41,42] which can be used to develop atomically thin optical devices for the generation and manipulation of GPVBs.

5. Conclusion

We have demonstrated the superposition of GPVBs in multiple channels with a single metasurface. The singularity distribution of the superimposed beam can be engineered by using different combinations of TCs. Moreover, the positions of singularities in the upper half and lower half of a beam can be modulated by introducing the initial phases in the metasurface design. In contrast to the conventional approach for the generation and manipulation of GPVBs, our work has provided a compact metasurface approach to complete this sophisticated task that is extremely challenging or impossible with conventional optics. This work can facilitate multichannel manipulation of GPVBs and realize asymmetric singularity modulation, which will open new opportunities for the investigation of intriguing applications of GPVBs in a wide range of areas such as quantum science and singular optics.

6. Experimental Section

The transmission-type bilayer metasurfaces consist of two layers: a top gold layer with rectangular holes, a layer of gold rectangular pillars surrounded by a positive resist, which is polymethyl methacrylate (PMMA) 950 A2. The electron beam lithography (EBL Raith-PIONEER, 30KV) is utilized to fabricate the designed metasurface. First, ITO coated

![Figure 6. Multichannel superposition of GPVBs. a) Simulated (left) and measured (right) intensity distributions of superimposed GPVBs in four channels. The positions of singularities are rotated with various angles, which are realized with different initial phases. b) Relationship between the rotation angles and the initial phases. c) Simulated (left) and measured (right) intensity profiles for GPVBs superpositions with different combinations of TCs, respectively. Various singularity distributions are obtained. The numbers of singularities in the superimposed beams are given here. Ch1: 4 (3 in the upper half and 1 in the lower half), Ch2: 6 (4 in the upper half and 2 in the lower half), and Ch3: 6 (5 in the upper half and 1 in the lower half). Ch4: 5 (3 in the upper half and 2 in the lower half). Ch: channel.](image-url)
SiO₂ substrates are cleaned in acetone for 10 min, followed by IPA for 5 min and then dried with a nitrogen gun. Next, 100 nm-thick PMMA film is spin-coated on the substrates, and then baked on a hotplate at 180 °C for 5 min. After that, nanopatterns are defined in the PMMA film by exposing it with an electron beam. The sample is then developed in the mixture of MIBK: IPA (1:3) for 45 s and cleaned in IPA for 45 s. Finally, a layer of gold film (40 nm) is deposited on sample using electron-beam evaporation. It is worth mentioning that a lift-off process was not required using this approach, which results in an overall less complex fabrication process.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
This project was funded by the Engineering and Physical Sciences Research Council (EP/P029892/1), the Leverhulme Trust (RPC-2021-145), DASA Advanced Vision project (DSTLX1000047844) and the Royal Society International Exchanges (R3)193046). Y.M. acknowledges the funding from the sponsorships of Jiangsu Government Scholarship for Overseas Studies, 2019. Y.I. acknowledges the support from the Ministry of Higher Education, Science, Research and Innovation (Thailand), and the Royal Thai Embassy in London (UK).

Conflict of Interest
The authors declare no conflict of interest.

Author Contributions
H.A. and Y.I. contributed equally to this work. X.C. and H.A. initiated the idea. H.A. and M.Y. conducted the numerical simulations. H.A. and Y.I. fabricated the samples and performed the measurements. H.A., X.C., M.A.A., G.S.B., and T.Z. prepared the manuscript. X.C. supervised the project with some input from G.S.B and T.Z. All the authors discussed and analyzed the results.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
grafted vortex beams, multiple channels, optical metasurfaces, optical perfect vortex beams, superposition of grafted vortex beams

Received: April 4, 2022
Revised: May 6, 2022
Published online: June 17, 2022

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