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Pervasive Externalities at the Population, Consumption, and Environment Nexus

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Growing concerns that contemporary patterns of economic development are unsustainable have given rise to an extensive empirical literature on population growth, consumption increases, and our growing use of nature's products and services. However, far less has been done to reach a theoretical understanding of the socio-ecological processes at work at the population-consumption-environment nexus. In this Research Article, we highlight the ubiquity of externalities (which are the unaccounted for consequences for others, including future people) of decisions made by each of us on reproduction, consumption, and the use of our natural environment. Externalities, of which the "tragedy of the commons" remains the most widely discussed illustration, are a cause of inefficiency in the allocation of resources across space, time, and contingencies; in many situations, externalities accentuate inequity as well. Here, we identify and classify externalities in consumption and reproductive decisions and use of the natural environment so as to construct a unified theoretical framework for the study of data drawn from the nexus. We show that externalities at the nexus are not self-correcting in the marketplace. We also show that fundamental nonlinearities, built into several categories of externalities, amplify the socio-ecological processes operating at the nexus. Eliminating the externalities would, therefore, require urgent collective action at both local and global levels.

The presence of externalities in economic activity is widely acknowledged today; yet, the focus has been on externalities associated with humanity's use of the natural environment (*1*, *2*). It is also widely appreciated that natural resources such as the global commons are underpriced, owing to those externalities. In contrast, consumption and reproductive externalities have been studied far less. The few empirical studies on this topic have found that those externalities can also be quantitatively important (*3*–*5*). In this paper, we characterize and classify reproductive and consumption externalities, relate them to environmental externalities, and show that they reinforce and are, in turn, reinforced by one another. For brevity we do not discuss production externalities, whose sources are, in any case, environment externalities.

Reproductive Externalities

Historical demographers have argued that the 17th-to-18th–century fertility transition in Northwest Europe is traceable to a then-growing practice of establishing a new household upon marriage (*6*). By saving or transfer, couples had to have sufficient resources to establish and equip their new household. Those requirements led to late marriages and meant that parents bore the cost of rearing their children. The total fertility rate (TFR) in England dropped to 4 in 1650 to 1700, when modern family-planning techniques were unknown and women were mostly illiterate.

In contrast, the TFR in sub-Saharan Africa remains over 5 today, and the region's population is expected to double to over 2 billion by 2050 (*7*). The average annual income in this region is currently 1200 international dollars (*8*). As sub-Saharan Africa has one of the highest TFRs in the world, yet is also one of the world's poorest regions, we have chosen to focus on aspects of African life that encourage high fertility and briefly compare these aspects with the changing situation elsewhere.

Pronatalist Institutions

Fosterage is commonplace in sub-Saharan Africa (*9*, *10*). In parts of West Africa, up to half the children may be living with their nonparental kin at any given time (*9*). Fosterage is not adoption; it does not break ties between parents and children. The institution affords a form of mutual insurance protection in a region where formal insurance markets are thin. But under fosterage, the private cost of rearing one's own children is lower than the societal cost of child-rearing. An argument identical to the one establishing that unmanaged commons are overexploited can be used to show that the institution of fosterage encourages excessive fertility (*11*, *12*).

Communal land tenure of the lineage social structure creates another problem of unmanaged commons, providing further incentive for men to procreate. Moreover, because conjugal bonds are weak, fathers in sub-Saharan Africa bear even less of the costs of child-rearing than they do in regions where polygyny is not practiced. Frequently, there is no common budget for the man and woman. Descent in sub-Saharan Africa is, for the most part, patrilineal and residence is patrilocal (the Akan people of Ghana are an exception). Taken together, patrilineality, polygyny, communal land tenure, and the institution of fosterage give rise to a set of externalities that promote fertility (*12*). Those social practices may be weakening and would be expected to decline under urbanization, but, to date, they have persisted and carry with them a momentum from the past.

A report by the United Nations Development Programme indicates that empowerment of women, a desirable end in itself, is associated with lower TFRs (*1*). Early marriage, particularly in the Sahel and North Africa, contributes to some of the highest TFRs in the world. Very few girls (only 1 in 100 in Niger, for example) complete secondary school. Family planning is not subject to the play of "free markets"; it is biased by restrictive laws, widespread misinformation, and rules not based on evidence (*13*–*16*). The unmet need for family planning is substantial. For example, the proportion of women in Malawi who either want to delay their next baby or stop having children altogether, but who are not using contraception, is ~25%. Women who have greater autonomy are better equipped to surmount the many barriers that often prevent easy access to family planning. When the barriers are few, as in Indonesia, the use of contraception and the TFRs among the highest- and lowest-income quintiles are similar (*15*). When the barriers are numerous, as in the Philippines, the poor both have more children and a greater unmet need for family planning.

Access to family planning can be increased relatively quickly compared with other approaches to lowering TFRs, such as improving women's education (although the alternatives may be synergistic). Forty percent of the world's population (including countries with TFRs as high as 6 as

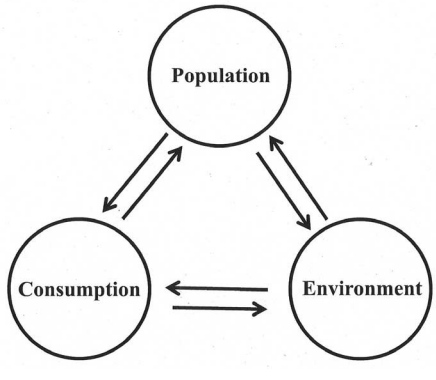

Fig. 1. Mutual influences amplified by externalities in the population-consumption-environment nexus.

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recently as 50 years ago) now has TFRs that are at or below replacement level. The aggregate demand for environmental resources is, in part, a function of humanity's population size. Whether world population reaches 8 billion or 10 billion in 2050 and whether it reaches 15 billion or 17 billion in 2100 will depend on small differences in average family size, which could be highly influenced by rebuilding the focus on family planning (*15*, *16*).

Conformity

In many spheres of life, traditional practices are perpetuated on account of a desire to conform (*17*–*19*). One's peer group matters, because it gives rise to another category of externalities. Procreation is not only a private matter but also a social signal, influenced by both family experiences and the cultural milieu. Conformism means that every household's desired family size is an increasing function of the average family size in the community. For instance, consider a society of N households. Let n_h be household h's desired family size and n^* the average family size of the community to which the household belongs. If people were conformist, n_h would be a piecewise increasing function of n^*, to be written as $n_h(n^*)$. In turn, as n_h affects n^*, each household inflicts an externality on all other households. If N is large, each of the externalities is definitely small, but the sum over all households can be substantial. In equilibrium, the average of all the households' desired n_h values would equal n^*; that is, $_{h=1}\Sigma^{N}[n_h(n^*)]/N = n^*$ (*18*, *20*).

To illustrate the structure of household preferences that display conformism, let $\mathbf{C_h}$ denote the quantities of goods and services h consumes (bold indicates that $\mathbf{C_h}$ is a vector of commodities), and let n_h be household size. We assume both are choice variables for household h (subject to budgetary and physiological constraints, of course). If $U_h(\mathbf{C_h},n_h)$ is a numerical representation of h's preferences over consumption bundles and family size, a simple form of conformist preferences is

$$U_h(\mathbf{C_h},n_h) = V_h(\mathbf{C_h},n_h) - \alpha_h(n_h - n^*)^2,\ \alpha_h > 0 \quad (1)$$

Here, V_h is an increasing function of $\mathbf{C_h}$ and, for small n_h, of n_h as well; α_h is a positive constant (*21*).

Whatever the basis of conformism, reproductive practices can persist even when their original purposes have disappeared, especially when misinformation about the safety of contraceptives is widely shared. So long as all others aim at large families (n^* is large), few households on their own would wish to deviate from the established practice, even when large family sizes prove to be an impediment to economic betterment, as they do in fragile ecosystems. But if a sufficiently large number of households were to restrict their fertility rates, others would do so as well (remember, n_h is an increasing function of n^*), improving their own prospects and those of their children. Thus conformism can harbor multiple, locally stable equilibria (*18*). If we now embed the structure of preferences in Eq. 1 in a dynamic model of consumption, saving, and reproduction, it can be shown that demographic history in the model economy is path-dependent. Fertility transitions can then be interpreted as disequilibrium phenomena, where societies move from high- to low-fertility equilibria. We consider one possible pathway for such transitions (*22*).

People differ in the extent to which they conform (i.e., α_h values differ across households). Inevitably, there will be those who, for one reason or another, experiment, take risks, and refrain from joining the crowd. Educated women are among the first to make the move toward smaller families (*23*). These women are the tradition-breakers, and they would be the ones to trigger fertility transitions, as others follow in time. A rapid pathway is the influence that newspapers, radio, television, and now the Internet play in transmitting information about other lifestyles. The influence of cultural exchanges via the media was pursued in a survey of fertility transitions in recent history (*4*). An analysis of a natural experiment in India has found that fertility rates declined in step after staggered introductions of cable television across the Indian states (*5*).

Breakdown of the Commons and the Added Need for Labor

The poorest countries are, in large part, biomass-based subsistence economies. Much labor is needed, even for simple tasks. Moreover, households in these poor nations do not have access to the sources of domestic energy available to households in advanced industrial countries, nor do they have water on tap. In arid regions, water supply is often not close at hand, nor is wood fuel easily accessible when forests recede. The relative prices of alternative sources of energy and water faced by rural households in poor countries differ from those faced by households elsewhere. In addition to cultivating crops, caring for livestock, cooking food, and producing simple marketable products, household members have to spend as much as 5 hours per day fetching water and collecting fodder and wood (*24*). These are complementary activities and must be undertaken on a daily basis if the household is to survive. Labor productivity is low, not only because manufactured capital and human capital are scarce, but also because natural resources are scarce. From the age of 6, children in rural households in the poorest countries mind their siblings and domestic animals; fetch water; and collect wood, dung (in the Indian subcontinent), and fodder. For the most part, these children do not attend school. The educational facilities in the typical school are woefully inadequate, and parents need their children's labor. In semi-arid regions of the Indian subcontinent and sub-Saharan Africa, children between 10 and 15 years old routinely work at least as many hours as adult males.

The need for many hands can lead to a destructive spiral. The tipping point can be one or more of many small changes. For example, in recent years mores that once regulated the use of the local resource base have changed in many parts of Asia and Africa. In the past, rural assets such as village ponds and water holes, threshing grounds, grazing fields, and woodlands were owned communally. Communities protected their local commons from overexploitation by relying on social norms, imposing fines for deviant behavior, and other means (*24*, *25*). But the very process of modernization can erode traditional methods of control, increased urbanization and mobility being one pathway (*24*). Social norms are also endangered by civil strife and the usurpation of resources by landowners or the state (*26*). Also, rules practiced at the local level have not infrequently been overturned by central fiat. A number of states in the Sahel imposed rules that effectively destroyed communitarian management practices in the forests. Villages ceased to have authority to enforce sanctions on those who violated locally instituted rules of use. State authority turned local common-property resources into open-access resources (*27*). Whatever the cause, as social norms degrade, parents pass some of the costs of children on to the community by overexploiting the commons. This is yet another instance of a demographic externality, but, in this case, its origins lie in deterioration in the management of local common-property resources (*18*, *28*).

Consumption Externalities

Consumption, both in total and in its composition, gives rise to externalities that have consequences for the present, as well as the future. Modern consumption practices that have dire environmental consequences, such as global climate disruption (externalities), have been much noted in the literature. Here, we focus on externalities that are internal to the drive we have for consumption. The choice of goods whose consumption creates the externalities we detail below depends on such factors as whether people are rich or poor, whether the poor in question live in poor countries or rich countries, and so on. But the particular drive for consumption we study here is a common human trait (*17*, *29*).

As social animals, we are competitive as well as conformists. We want to attain status in our community in certain ways, yet we simultaneously strive to be like others in different ways.

Competitive Consumption

In his classic work on the Gilded Age, Veblen (*30*) spoke of "conspicuous consumption" so as to draw attention to types of consumption that serve as status symbols. Veblen's notion of status has been extended by social scientists to cover the tendency of people to try to outdo one another (*31*). Here, we call this drive "competitive consumption." To formalize, let $\mathbf{C_h}$, as before, denote a bundle of consumption goods in an N-person society. We now introduce a further good, denoted by X: the average consumption

level of which, in the community, is X^* (i.e., $X^* = {}_h\Sigma X_h/N$). If $U_h(\mathbf{C_h},X_h,X^*)$ is a numerical representation of h's preferences, consider the functional form (*32*)

$$U_h(\mathbf{C_h},X_h,X^*) = V_h(\mathbf{C_h},X_h/X^*) \quad (2)$$

Here, V_h is an increasing and concave function of each component of $\mathbf{C_h}$ and X_h/X^* (*33*).

Equation 2 reflects competitive preferences over X, which give rise to "rat races." In a free market, every household tries to beat all others in their consumption of X in a losing proposition, for no one is better off: In equilibrium everyone works harder so as to purchase and consume more X than they would if they all agreed to work less hard and consume less X (*3*, *32*). If N is large, the effect of household h's choice of X on X^* (the externality) is no doubt small, but the sum of the externalities can be shown to be non-negligible. The process creates a problem of the commons, albeit in a different sphere from common-property resources—structurally, however, they are the same. They both reflect aspects of the well-known prisoners' dilemma in game theory.

Competitive consumption (hosting expensive wedding ceremonies and birth celebrations) in subsistence economies may not have repercussions on the global environment, but it hinders the prospects the poor may have for escaping poverty (*34*). In rich societies, competitive consumption has further adverse consequences. For instance, automobiles make transportation simple and easy, but choices of the make and vehicle use are driven in many ways by the competitive urge (*35*). Moreover, car use is dependent on an underpriced resource: oil. If we add consumption habits into the equation and a growing complementary infrastructure (gas stations, expanded network of highways), we have a spiraling exploitation of natural capital and the environmental externalities that come allied to it (*12, 15, 16*). Environmental problems of this kind have certainly originated in today's rich countries, but the consumption of conspicuous, resource-intensive goods and services is known to be increasing in developing countries also (*2, 36*).

Conformism

Because people try to find ways to relate to one another, they also adopt patterns of consumption that reflect a desire for conformity, not competition (*17*, *29*). Fads and fashions are brief occurrences, but conformist consumption can be persistent if it serves the need for social belonging—hence the term "relational goods" to characterize commodities that serve as an anchor for the desire and need to belong (*37*, *38*).

To illustrate the character of social consumption, let $\mathbf{C_h}$, as before, denote a bundle of consumption goods. We now introduce an additional commodity, labeled X, which serves as a relational good. The average consumption level of X in the community is X^*. If $U_h(\mathbf{C_h},X_h,X^*)$ is a numerical representation of household h's preferences, we return to the formulation of conformism in reproductive decisions to construct U_h as

$$U_h(\mathbf{C_h},X_h,X^*) = V_h(\mathbf{C_h},X_h) - \alpha_h(X_h - X^*)^2,\ \alpha_h > 0 \quad (3)$$

Here, V_h is an increasing function of each component of $\mathbf{C_h}$ and X_h (*33*).

Conformism leads to a different social dynamic from competitive consumption. The social environment that characterizes it is not a prisoners' dilemma but a "coordination game" (*39*). In contrast to a prisoners' dilemma, coordination games possess multiple equilibria, which can be ranked in terms of societal well-being. To confirm this in a simple manner, consider an extreme version of Eq. 3

$$U_h(\mathbf{C_h},X_h,X^*) = V_h(\mathbf{C_h}), \text{ subject to } X_h = X^* \quad (4)$$

The idea underlying U_h in Eq. 4 is that some consumption choices (over X in this instance) reflect preferences only for consuming as others do, and not for any particular preference for the personal consumption of the goods in question (*40*).

Equation 4 makes clear that, as with conformism in the sphere of reproduction, a community may coordinate to settle on one of many alternative behavior patterns that are ranked identically by all individuals. Presumably, there would be equilibria that are more intensive than others in their use of underpriced natural capital. Consumption choices in the former type of goods inflict adverse externalities on other communities.

As the problem besetting the community is one of coordination, the collective assurance that people will choose a preferred level of X would suffice to improve consumption patterns. If each person can be persuaded to believe that others will reduce their consumption of X, every person will follow suit. One way of achieving that assurance would be to nudge one another to opt for a targeted alternative.

Environmental Externalities

Environmental externalities have been much discussed in the literature (*2*). Here, we focus on detrimental externalities. Two broad types may be contrasted: unidirectional and reciprocal. Under unidirectional externalities, one agent (or a set of agents) inflicts an externality on another (or others). Classic examples of unidirectional externalities involve pollutants transported downstream by wind and water. As is well known, the discharge of pollutants is excessive in the presence of such externalities.

Exports of primary products can come allied to domestic unidirectional externalities, a fact that has been rarely studied empirically. Logging in upstream watersheds gives rise to soil erosion and increased fluctuations in the supply of water downstream (the externalities). If compensation were not paid to downstream farmers and fishermen for the loss of water and decimation of estuarine fish stocks, the export price of timber would be less than its social price (commonly known as "shadow price"). Therefore, the export would contain a hidden subsidy, amounting to a transfer of wealth to the importing country from farmers and fishermen in the exporting country.

Under reciprocal externalities, each party inflicts an externality on all others, as in the case of unmanaged common property resources. To manage the commons well means eliminating the externalities (*25*). Local communities have been known to manage spatially contained commons by the institution of norms of conduct and the imposition of fines and social sanctions (*24*, *25*). Unfortunately, the same cannot be said in regard to the global commons. It is widely understood today that unmanaged commons are overexploited. Among these unmanaged commons, the atmosphere as a sink for carbon has been studied the most in recent years (*1*, *2*), but the oceans consist of yet another class of global commons. Previously, we noted that local institutions have been known to degrade under pressure from markets and state intervention. Taking local and global commons together, nature's hidden subsidies have likely risen in recent decades.

Difficulties in Enacting Policies to Counter Externalities

Popular discourses on economic growth and development frequently assume that nature is a fixed, indestructible factor of production. Advanced textbooks on economic growth and development are based on a similar thesis. But nature consists of degradable resources. Agricultural land, forests, watersheds, fisheries, fresh water sources, estuaries, the atmosphere, and, more generally, ecosystems are self-regenerative capital assets, but they suffer from depletion or deterioration when they are overused or toxified.

Environmental externalities are pervasive because property rights to prominent classes of natural capital are difficult to enforce and, worse, challenging to define. One reason is their mobility: The wind blows, rivers flow, fish swim, deer flee, birds and insects fly, and even earthworms are known to move. Moreover, global climate change and the deteriorating state of the world's oceans indicate that substitution possibilities between produced capital and human capital, on one hand, and vital forms of natural capital, on the other, are limited (*41*). Official statistics on national income give the impression that the natural environment is of small importance (the share of agriculture in national income in the United States is only 2 to 3%, so there is no reason to worry), but official statistics are built on market prices, not prices that reflect the social worth of natural capital. If shadow prices were to be used in economic statistics, the decomposition of national income into its various components would look quite different (*42*, *43*). The reproductive and consumption externalities we have outlined here

have a different origin, having to do with our psychological needs and drive.

Nonlinearities

Our account of reproductive and consumption externalities provides an explanation for why growth in population is a point of special concern in poor countries, whereas in rich countries with TFRs below 1.8, the focus should be wasteful consumption (*15*). We have shown not only that there is feedback between each node at the population-consumption-environment nexus (Fig. 1), but that externalities at each node amplify the feedback. Taken together, these factors create the unsustainable stresses on nature that have been recorded in recent years (*44*). The harmful effects of those stresses are made urgent by the presence of nonlinearities in the coupled processes at work. As the nonlinearities involve positive feedback, the stresses are yet further amplified and act more quickly (*45*, *46*).

Nonlinearities are ubiquitous in the processes governing Earth; this is a central message of the environmental sciences (*46*). It is also known that competitive markets cannot exist in a world where production and consumption possibilities (including the use of natural capital) are subject to substantial nonlinearities (*47*). Modern economics has shown that nonlinearities are inevitable in social systems suffering from harmful environmental externalities (*48*). Hence, the externalities associated with competitive consumption generate yet another class of nonlinearities. Creating competitive markets for externalities as a way to eliminate their unintended consequences is, thus, not an option (*47*, *48*). Nonmarket institutions are a necessary complement to customary markets. The creation of such institutions requires collective action among affected parties, but for that to come about, the parties need to be aware of the character of those externalities. This is beginning to happen in the case of a handful of nature's commons (*1*, *2*)—for example, the global climate and the oceans—but, to date, there have been few attempts to estimate the magnitude of the reproductive and consumption externalities we have classified in this work.

Nonlinearities in socio-environmental systems are increasingly coupled with one another across space and time through trade in goods and services, which has aggravated problems by making individual risks overly correlated with one another (*49*). Because nonlinear systems can undergo regime shifts, the time it takes for a society to recognize that part of its system is near a tipping point until fully tipping into an unpalatable state is increasingly short. Currently, more than 45% of the 45 billion to 60 billion metric tons of carbon that are harnessed annually by terrestrial photosynthesis is being appropriated for human use (*50*). Due in large measure to that, 15 of the 24 major ecosystem services examined in the Millennium Ecosystem Assessment (*44*) were found to be either degraded or currently subject to unsustainable use. Crude calculations suggest that if the 5.7 billion people in poor and middle-income countries were to match the consumption patterns of the 1.3 billion people in the rich world, at least two more Earths would be needed to support everyone on a sustained basis (*51*). The consensus among demographers is that world population will be 9.5 billion or more by 2050. Should that prove accurate, the demands made on Earth will prove to be even more unsustainable.

Technological Change

People are known to insist that technology can be relied on to come to humanity's aid (*52*), but new technologies do not come out of thin air. Innovators respond to incentives, and institutions matter. The underpricing of natural capital, for example, influences the direction of research and development, and the latter influences the character of technological change. Because nature's services are underpriced in the market, innovators have little reason to economize on their use. We should not be surprised when new technologies are rapacious in the use of natural capital. The cumulative adoption of such technologies and practices over the centuries has locked us into an infrastructure that will prove very hard to dislodge.

Evidence from the past tell us, however, that people have often responded successfully to growing economic stress by inventing new ways of doing things (*53*). After all, today's rich countries were poor not so long ago. But both evidence and the theoretical underpinning to that evidence tell us that successful response cannot be guaranteed. For example, in the face of population pressure in Bangladesh, small land-holders have periodically innovated so as to intensify agricultural production. However, this has resulted in imperceptible improvement in the standard of living and an increase in landless households (*54*), the latter probably owing to the prevalence of distress sales of land. By analogy, the image that comes to mind is of people walking up an escalator that is coming down at the same speed.

That image has been sharpened in recent years by the empirical discovery that the persistence of poverty and continued loss in biodiversity are closely connected in parts of sub-Saharan Africa (*55*). Moreover, recent archaeological studies showing that a number of societies in the distant past collapsed, owing to degradation of the local environmental-resource base, provide indirect evidence of the contemporary presence of alarming positive feedback within the population-consumption-environment nexus (*56*).

Conclusion

Although their magnitudes are likely to vary across societies, owing to differences in societal histories, institutions, customs, and ecologies, the reproductive and consumption externalities we have identified here share marked commonalities. Moreover, our analysis has uncovered reasons why technological innovations since the Industrial Revolution have been rapacious in their reliance on natural capital. We have shown that the externalities studied in this paper are not self-correcting. Hence, our analysis points to a spiraling socio-environmental process, giving credence to the presumption that the pattern of contemporary economic growth is unsustainable.

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REPORTS

Near-Field Interference for the Unidirectional Excitation of Electromagnetic Guided Modes

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Wave interference is a fundamental manifestation of the superposition principle with numerous applications. Although in conventional optics, interference occurs between waves undergoing different phase advances during propagation, we show that the vectorial structure of the near field of an emitter is essential for controlling its radiation as it interferes with itself on interaction with a mediating object. We demonstrate that the near-field interference of a circularly polarized dipole results in the unidirectional excitation of guided electromagnetic modes in the near field, with no preferred far-field radiation direction. By mimicking the dipole with a single illuminated slit in a gold film, we measured unidirectional surface-plasmon excitation in a spatially symmetric structure. The surface wave direction is switchable with the polarization.

Interference is the cornerstone of various phenomena in nature, enabling numerous applications. In optics, it is intensively used in microscopy, stellar measurements, spectroscopy, and communication technologies, among many others, and is the basis behind the concepts of reflection, refraction, and light bending (*1*, *2*). Typically, interference occurs as a result of the relative phase lag of different propagating waves. By contrast, nanophotonics—the branch of optics studying the interaction of light with subwavelength nanoscale structures—deals inherently with phenomena that occur via near-field interactions before appreciable phase lags can be accumulated (*3*). A radiationless form of interference in the near field (*4*) is behind new exciting applications such as the focusing of evanescent components to achieve subwavelength resolution in imaging (*5*–*8*). Near-field interference achieved through the full coherent control of the phase and amplitude of excitation light allows asymmetric spatial field localization (*9*, *10*) and selection of propagation paths at intersections of waveguides (*11*).

We demonstrate near-field interference by considering a single source of radiation coupled to a mode with a vectorial structure of electromagnetic field. With an additional degree of freedom provided by the vectorial character of the field, control over the near-field interference can be achieved. We show that an elliptically polarized dipole can produce destructive or constructive interference of different evanescent components in its near field and, as a result, excite electromagnetic modes in neighboring material structures, such as dielectric and plasmonic waveguides and diffraction gratings, with a controlled directionality of propagation.

Recently, several solutions for the directional excitation of surface plasmon polariton (SPP) waves (*12*, *13*) have been proposed, including a backside-illuminated slit near a surface Bragg grating (*14*), the use of asymmetric slanted gratings (*15*) and chirped gratings (*16*), tilted-angle illumination of slits and gratings (*17*, *18*), or the illumination of nearby, compact nanoantennas (*19*). Directional extraction of light from localized emitters with nanoantennas (*20*), emission directionality of thermal sources coupled to SPPs (*21*), and directional coupling to planar dielectric photonic waveguides (*22*) have been demonstrated. All of the above approaches have a resonant nature and rely on the careful selection of the wavelength and geometrical parameters of the structure, with the direction of excitation determined by an asymmetry of the structure and/or the incident light direction. Near-field dipolar interference provides a fundamentally different approach to unidirectional guided wave excitation with broadband (nonresonant) characteristics and the opportunity to achieve polarization-tunable directionality.

The phenomenon of unidirectional excitation can be understood by considering a dipole placed at a subwavelength distance d from a waveguide surface—for example, a dielectric slab or a single metal-dielectric interface (Fig. 1A). The high–spatial-frequency components of the dipole radiation allow the excitation of guided modes in the waveguide. The fundamental principle behind the effect of unidirectionality is the selective vectorial excitation of the electric field of the waveguide mode, dependent on the emitted polarization. At the location of the waveguide immediately below the dipole, the vertically oriented component of the dipole is coupled to the transverse

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