Fireworks for the information age

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What is the information content of a molecule? What is the data transmission rate associated with a chemical reaction? In contemplating such questions, Thomas et al. in this issue of PNAS (1) arrive at an interesting prototype device that stores and retrieves information by using only chemistry and chemical processes. This combination of information technology and chemistry, in a new field that Thomas et al. call "infochemistry," provides unusual strategies for communication and data storage with the potential for important practical applications.

Information processing is central to nearly all forms of modern technology. The most well-established systems for data storage and retrieval are based on electronic, photonic, and/or magnetic phenomena. Flash memory, for example, uses the control of charge on a floating gate to modulate the threshold voltage of a metal oxide field effect transistor, as a means for writing and reading information (2). Hard drives use inductive/magnetoresistive effects to record/extract data in the form of spatial patterns of magnetization on a spinning disk (3). Magneto-optical drives (4) manipulate magnetization at somewhat larger scales with heating induced by focused light and uniform magnetic fields. Information retrieval occurs by monitoring changes in reflectivity, much like a purely optical drive (5). Some of the newest and most powerful technologies use holograms written into polymer films to achieve unprecedented storage densities and retrieval rates (6).

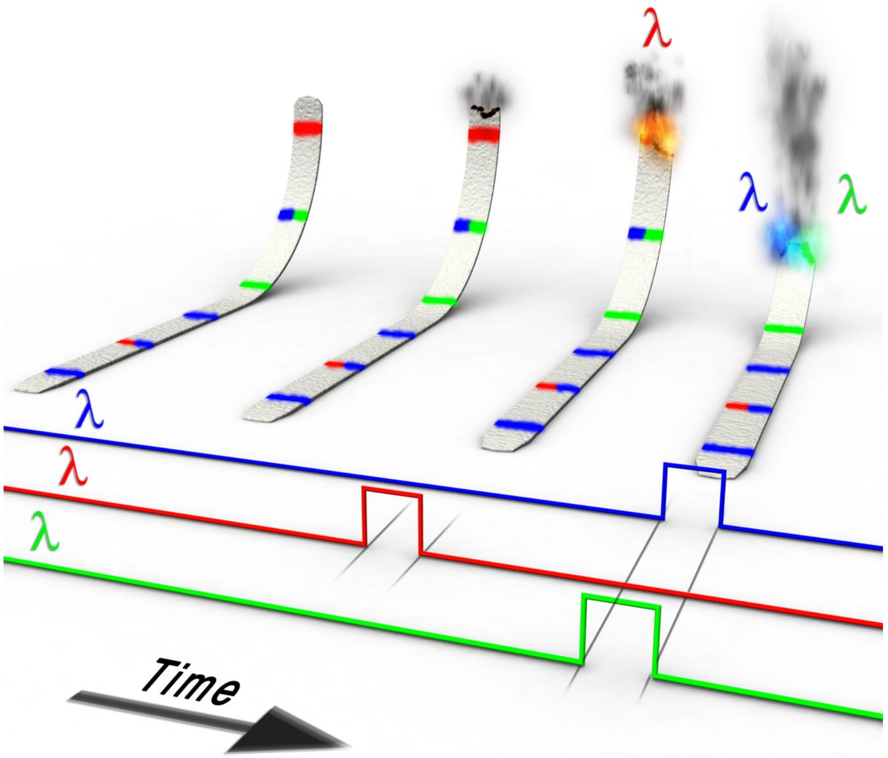

Fig. 1. Schematic illustration of a device that stores and reads out information based only on chemistry and chemical reactions, as an example of the principles of infochemistry. Here, printed patterns of alkali metal salts on a thin strip of NC form an infofuse that, when ignited at one end, emits a pulsed sequence of colored light that can transmit a message. This first demonstrator provides a combination of performance parameters that cannot be achieved easily by using established information technologies, making it suitable for use, for example, in demanding environments where access to electrical power is also limited.

Although these and related approaches offer spectacular levels of functionality at very low cost per bit, there may be opportunities for alternatives; biology, where information is encoded in base-pair sequences of DNA and transmitted via RNA, represents a compelling existence proof. This bio-inspired idea of using molecules themselves as a form of information technology could lead to entirely new classes of devices. Early work on DNA computers, in which base-pairing in large numbers of DNA provide parallel routes for examining many outcomes for certain classes of problems, might be viewed as among the first attempts to exploit such concepts in a technology (7). More recent, related embodiments provide paths in which input and output information is in molecular form; devices that monitor and respond to biomolecular species represent impressive examples (8). These approaches, however, focus on information processing, rather than storage and communication; they are also slow and often require nonchemical means to program the systems and read out the results. Although the ideas of infochemistry introduced in Thomas et al.'s article (1) have some features in common with previous work, the emphasis is instead on outcomes that provide direct alternatives to the sorts of devices described in the previous paragraph. Flares are the simplest abiotic embodiments of the concepts of infochemistry, where chemical reactions transmit information on location and serve as distress signals. Fireworks can be considered as a similar class of technology, in which the transmitted messages are abstract, but valuable nevertheless. Thomas et al. (1) show how advanced chemistries and materials processing technologies can yield qualitatively more sophisticated versions, capable of storing and communicating alphanumeric messages, in formats that are compatible with further scaling. In particular, they demonstrate their ideas of infochemistry in a type of device that they call an "infofuse": an ink jet-printed pattern of different alkali metal salts on a thin strip of nitrocellulose (NC). Igniting an end of such a structure leads to controlled burning that thermally excites atomic emission from the metals to produce short pulses of colored light in specific, programmed time sequences. The chemistry of the salts and their spatial

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configurations encode the information. The chemical reactions associated with burning affect the readout and transmission, in a form of time and wavelength division multiplexing that has features in common with free space lightwave communication systems (9). Fig. 1 provides a schematic illustration.

Thomas et al. (1) consider carefully the operational aspects of these infofuses to yield workable designs. First, the choice of NC as the substrate provides a hot (1,000 °C) flame, but with little soot or char that would otherwise generate incandescence sufficient to overwhelm the emission from the metallic salts. The NC also burns in very controlled rates in the range of ≈cm/s, with only ≈10% deviations from the mean, for reproducible readout. Second, the alkali metal salts generate strong, spectrally-narrow emission, at intensities that are more than an order of magnitude larger than background associated with adventitious sodium in the NC. The narrow emission lines enable the use of spectral-filtering techniques to improve the signal-to-noise ratios to provide multiple channels for communication. The wavelengths span the blue (copper) to the near-infrared (potassium rubidium and cesium), corresponding to a range that is much wider than that used for conventional optical communication networks. Third, Thomas et al. exploit 3 different features to encode information: the duration, spacing, and intensity of emission. The first two can be controlled by the pattern of the salts; the third can be controlled by the amount. In present designs, variability in the position of the burn front, and not the pattern resolution, limits the shortest durations and spacings. As a means to mitigate the effects of this variability and uncertainties in the amounts of the salts and the positions of the fuses relative to the detectors, Thomas et al. exploit a fourth design strategy: they use emission from sodium as an internal standard to measure relative intensities. Infofuses with all of these features can transmit short, alphanumeric messages and can also report the concentration of a representative analyte (lithium) with pulse frequencies of up to ≈10 Hz and errors in the intensities of the pulses of <10%. Further improvements might emerge from more detailed understanding of the physics and chemistry of the combustion process, aspects of which might also have relevance to apparently distant fields such as the production of energy by burning of fossil fuels. These features further enhance the appeal of research.

Infochemistry devices can be naturally integrated with sensors for chemical and biological agents.

For a first demonstrator, Thomas et al. (1) achieve an interesting combination of performance parameters in their infofuses: self-powered operation; bit rates of up to several tens of hertz; omnidirectional transmission with a range of tens of meters, or more; lightweight, rugged, flexible construction; and simple fabrication, with the potential for low cost. Although any one or several of these characteristics can be easily exceeded with conventional technologies, realizing all of them in a single system would be difficult. Therein lies the value of infochemistry in general and infofuses in particular; they provide a set of features that could open up new opportunities in information technology. Thomas et al. speculate, for example, that infochemistry devices can be naturally integrated with sensors for chemical and biological agents, in a way that can combine detection with readout and transmission, in a single, simple system. They might also be combined directly with lenses, waveguides, and thermal and photodetectors to yield hybrid devices whose function relies only partly on infochemistry. Exploring these possibilities and studying fundamental issues associated with scalability of size, information density, and transmission rates represent exciting future directions for research in this nascent field.

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