We now understand in some detail how the combined effects of transport, chemical ozone production, and catalytic ozone loss control ozone during the annual cycle of stratospheric conditions. The summer ozone decreases at high latitudes will persist in the future because natural (NO_x) rather than human-induced (halogen) species are primarily responsible for ozone destruction there. In contrast, the winter-spring ozone destruction will gradually lessen in the next decades as halogen emissions steadily decrease—barring other changes to the stratosphere such as major cooling of this region due to greenhouse gases (*14*). Although the summer and winter polar stratospheres have similar potential for chemical ozone destruction, differences in sunlight and temperature keep their ozone abundances poles apart.

References and Notes

1. WMO (World Meteorological Organization), Scientific Assessment of Ozone Depletion: 1998 (Global Ozone Research and Monitoring Project Report No. 44, WMO, Geneva, 1999).
2. J. C. Farman *et al.*, *Q. J. R. Meteorol. Soc.* **111**, 1013 (1985).
3. L. M. Perliski, S. Solomon, J. London, *Planet. Space Sci.* **37**, 1527 (1989).
4. C. Brühl, P. J. Crutzen, J.-U. Grooss, *J. Geophys. Res.* **103**, 3587 (1998).
5. R. J. Salawitch *et al.*, *Science* **261**, 1146 (1993).
6. D. W. Fahey *et al.*, *Nature* **363**, 509 (1993).
7. D. R. Hanson, E. R. Lovejoy, A. R. Ravishankara, *J. Geophys. Res.* **101**, 9063 (1996).
8. R. S. Gao *et al.*, *Geophys. Res. Lett.* **26**, 1153 (1999).
9. G. B. Osterman *et al.*, *ibid.*, p. 1157.
10. T. J. Dransfield *et al.*, *ibid.* **25**, 687 (1999).
11. S. S. Brown, R. K. Talukdar, A. R. Ravishankara, *Chem. Phys. Lett.* **299**, 277 (1999).
12. ———, *J. Phys. Chem.* **103**, 3031 (1999).
13. M. P. Chipperfield, *J. Geophys. Res.* **104**, 1784 (1999).
14. M. E. Summers, *Science* **284**, 1783 (1999).
15. R. D. Bojkov and V. E. Fioletov, *J. Geophys. Res.* **100**, 16537 (1995).

16. The authors acknowledge helpful discussions with M. P. Chipperfield, R. S. Gao, S. R. Kawa, R. J. Salawitch and S. Solomon. We are grateful to W. Randel for providing the annual cycle in TOMS ozone values shown in the first figure.

PERSPECTIVES: GENETICS

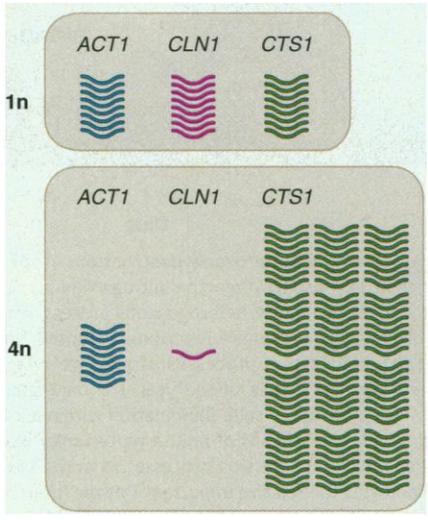
Polyploidy—More Is More or Less

Philip Hieter and Tony Griffiths

Biologists tend to think of the normal ploidy (number of complete chromosome sets) of cells as either diploid (2n) or haploid (n). Yet examples of polyploidy (more than two sets of chromosomes) abound among plants and animals (*1*, *2*). The bananas we eat are triploid (3n); wheat is hexaploid (6n). At least half of the natural species of flowering plants are polyploid and, although polyploid animal species are less common, some groups, such as salmonid fish and certain amphibians, have clearly evolved by doubling or tripling their ploidy.

Cells differing only by their ploidy are identical in terms of DNA sequence information and relative gene dosage, and yet are often quite different in terms of physiology, morphology, and behavior. How can this be so? A report by Galitski *et al.* on page 251 of this issue (*3*) provides a satisfying answer. In a convincing demonstration of the power of DNA chip technology, these authors found that yeast (*Saccharomyces cerevisiae*) with different ploidies had different patterns of gene expression. Their findings provide definitive evidence for a ploidy-driven mechanism of gene regulation that may be important in a variety of biological states.

Changes in ploidy during cell differentiation appear to be important in development. Almost all plants and animals generate specific sub-populations of polyploid cells by endoreduplication cycles (DNA replication in the absence of cell division) during tissue-specific differentiation (*4*). For example, the ploidy of megakaryocytes (the cells that produce blood platelets) ranges from 16n to 64n; that of cardiomyocytes (heart muscle cells) from 4n to 8n; and that of hepatocytes (liver cells) from 2n to 8n. A related phenomenon, polyteny (chromosomes consisting of multiple strands), is also found during development, the best-known example being the giant salivary gland chromosomes of insects. Many cancer cells are polyploid, raising the still unresolved issue of whether an increase in ploidy contributes to, or is a consequence of, tumor development (*5*).



Ploidy paradox. Yeast strains that differ only in their ploidy show different patterns of gene expression. The mRNA levels (wavy lines) for three genes are shown in haploid (1n) and tetraploid (4n) yeast strains. *ACT1*, like most genes, is not affected by an increase in ploidy. A small subset of genes is dramatically repressed (for example, *CLN1*) or induced (for example, *CTS1*) in response to increased ploidy. Changes in ploidy also affect the expression of many more genes, but not as dramatically.

Ploidy also varies by a factor of 2 during mitotic (G_1 versus G_2 phase) and meiotic (germ cell versus gamete) cycles of cell division. Mitotic cells double their ploidy during DNA synthesis, and ploidy is restored at cell division. Meiotic cells reduce their ploidy by half during gametogenesis, and ploidy is restored upon fertilization. Thus, changes in ploidy commonly occur both in normal states (during differentiation in multicellular organisms, in the evolution of species, and in the DNA replication and cell division of mitosis and meiosis) and under abnormal conditions such as disease.

The elegance and rigor of the experimental design in the Galitski *et al.* study could only be achieved in yeast at this point in time. First, using genetic trickery and a clever series of manipulations, a perfectly isogenic (genetically identical) set of yeast strains differing only in ploidy (1n, 2n, 3n, 4n) were constructed and compared. Second, yeast is the only eukaryotic organism for which whole-genome expression analysis (that is, the identity of each expressed gene and its level of expression) can be determined completely in a single experiment.

The investigators used DNA chip technology to analyze mRNA levels for all genes in yeast strains that varied only in their ploidy. They then searched the data for genes whose expression, relative to total gene expression, increased or decreased as the ploidy changed from haploid to tetraploid. Most genes showed no change in mRNA levels relative to total RNA. However, when the investigators introduced a stringent cutoff requiring a 10-fold difference in gene expression be-

The authors are in the Departments of Medical Genetics and Botany, University of British Columbia, Vancouver, British Columbia, Canada. E-mail: hieter@cmmt.ubc.ca

tween haploid and tetraploid yeast strains, they unearthed 10 genes that were ploidy induced and 7 genes that were ploidy repressed. For example, comparing gene expression in tetraploids versus haploids (see the figure), mRNA levels for *CLN1* (a cell cycle protein, G_1 cyclin) were about a factor of 10 lower whereas those for *CTS1* (a protein involved in the separation of mother and daughter cells) were about a factor of 10 higher. These 17 genes are at the top of a large group of genes, most of which are less dramatically up- or down-regulated in response to increased ploidy.

Polyploid cells and tissues are usually larger and more metabolically active than their diploid counterparts. These differences increase with increasing ploidy, yet there is no theory to explain the functional significance of polyploidy (*6*). It is known from yeast genetics that yeast cells expressing low levels of G_1 cyclins delay "START" (the entry point into the cell cycle) and, therefore, achieve a greater cell size during G_1 phase. The ploidy-dependent repression of G_1 cyclins observed by Galitski and colleagues may explain the greater cell size associated with higher ploidy. As most polyploid cells are bigger than their diploid brethren, the insights provided by yeast may be applicable to other organisms. The authors made similar satisfying correlations for phenotypes associated with ploidy-dependent induction of *CTS1* (cell adhesion), and repression of *GIC2* (cell shape) and *FLO11* (invasiveness). In comparison to haploids, which invade an agar substrate efficiently, tetraploids are poorly invasive. By introducing *FLO11* on a multicopy plasmid into tetraploid yeast and restoring their invasiveness, Galitski and co-workers elegantly established a direct connection between loss of the invasive phenotype in tetraploids and the repressive effect of increased ploidy on *FLO11* expression.

The ability of the yeast gene expression data to explain these biological phenomena is gratifying and lends support to the biological importance of ploidy-dependent gene regulation. How gene transcription responds to ploidy is unclear, but a variety of mechanisms can be envisioned. An increase in total cellular DNA results in a corresponding increase in nuclear size and a reduction in the ratio of nuclear surface area to nuclear volume. Galitski *et al.* suggest that these physical changes may affect the import and final concentration of transcription factors and regulatory proteins within the nucleus, thus accounting for global changes in gene transcription profiles. Whatever the molecular explanation might be, the existence of a ploidy-dependent mode of gene regulation has been firmly established, and one can predict with certainty that biological systems will take advantage of this novel mode of gene regulation wherever possible.

References

1. V. Ya. Brodsky and I. V. Uryvaeva, *Genome Multiplication in Growth and Development* (Cambridge Univ. Press, Cambridge, 1985).
2. T. R. Gregory and P. D. Hebert, *Genome Res.* **9**, 317 (1999).
3. T. Galitski *et al.*, *Science* **285**, 251 (1999).
4. I. Royzman and T. L. Orr-Weaver, *Genes Cells* **3**, 767 (1998).
5. C. Lengauer, K. Kinzler, B. H. Vogelstein, *Nature* **396**, 643 (1998).
6. T. Cavalier-Smith, *J. Cell Sci.* **34**, 247 (1978).

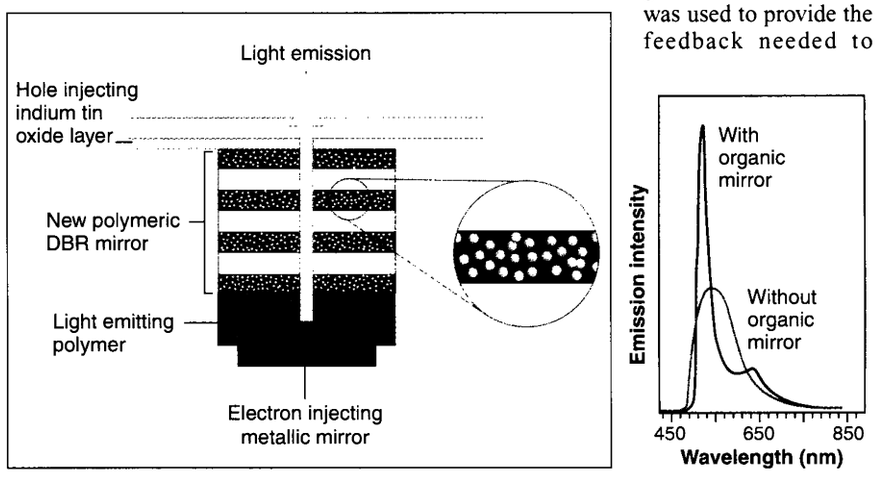
PERSPECTIVES: OPTOELECTRONICS

Reflections on Polymers

William L. Barnes and Ifor D. W. Samuel

A decade ago, it was discovered that semiconducting organic polymeric materials could be made into light-emitting diodes (LEDs) (*1*). When electrons and holes injected into a suitable polymer capture each other, they form an exciton, which can then decay to produce a photon—light. Despite continuing controversy over some of the details of exciton generation and recombination, so much progress has been made that Philips Components now has a pilot-scale production plant aiming for polymers to take part of the estimated $40 billion per year displays market. The properties of the emitted light can be controlled by placing the polymer layer between two mirrors to form a tiny cavity, known as a microcavity. To date, inorganic materials have been used to make these mirrors (*2*). Now, Ho and colleagues (*3*) show on page 233 of this issue that control of the emitted light can be achieved using layered structures of semiconducting organic polymers .

The attraction of these semiconducting organic materials is twofold. First, at the molecular level their composition may be readily controlled to adjust their charge-transport properties (*4*) and the color of their emission (*5*), both of which are vital for commercially viable display devices. Second, these tunable polymers can be processed in solution. It has recently been shown that organic LEDs can be produced by ink-jet printing (*6*) and spin cast onto flexible substrates (*7*), emphasizing the potential their easy processing confers. Many of the organic LEDs studied to date are composite optical microcavity structures (*8*).The light-emitting polymer is confined to a thin (~100-nm) layer sandwiched between two inorganic mirrors that often also serve as the charge-injecting contacts (see the figure). Microcavities enable control over the optical properties of the emitted light. Recently, a layered inorganic dielectric mirror was used to provide the feedback needed to



Polymer mirrors. By sequentially spinning polymer layers that are alternately doped with and free of 5-nm silica beads, a charge-transporting microcavity mirror is formed; DBR, distributed Bragg reflector (**left**). Injection of electrons and holes results in the emission of light, the spectrum of which is modified by the polymeric mirror [**right**, modified from (*2*)].

W. L. Barnes is in the School of Physics, University of Exeter, Exeter, EX4 4QL, UK; I. D. W. Samuel is in the Department of Physics, University of Durham, Durham DH1 3LE, UK. E-mail: w.l.barnes@ex.ac.uk and i.d.w.samuel@durham.ac.uk