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COVER Conversion of images into digital form is one aspect of computer vision. Once digitized, an image can be processed, manipulated, and interpreted. The matrix of numbers is the numerical representation of the light and dark regions within the square border around the woman’s eye. The articles in this issue survey developments in computer vision, robotics, parallel processing, and natural language processing. See editorial, page 1189, and articles, pages 1227 to 1254. [Cover by Julie Cherry; digital image of Sarah Bernhardt courtesy of Azriel Rosenfeld]

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Frontiers of Computer Science

Computer scientists work in an interdisciplinary realm between mathematics and engineering. Subsequent to the revolution in personal computing, the tangible benefits of this fertile interaction have tended to concentrate public attention on quantitative progress: cheaper memory, higher resolution graphics, increased storage capacity, and so forth. But computer scientists have long been toiling at the conceptual frontiers. The articles in this issue give a sample of the qualitative as well as quantitative progress being made.

One outpost at the frontier is the effort to build autonomous robots that function in unpredictable environments. The present generation of machines works well, but only if their tasks are well-defined (painting) and their surroundings are more or less unchanging (they are bolted to the factory floor). Traditional robotics relies on central modules that sequentially perceive the world, model it, and then plan and execute some action. Brooks describes a robot architecture in which the overall behavior of the machine is controlled by a network of simple computational elements operating concurrently. The addition of elements layer by layer yields the complex behavior needed for useful work. An advantage is quicker responses to a changing world. As the author himself points out, much work is needed before the performance of these systems can be fully evaluated.

Microprocessor performance is a subject dear to the hearts of computer users everywhere, yet how much more power can be squeezed out of present and future chips? One route is to use many independent processors in parallel. Another avenue, discussed by Fisher and Rau, is instruction-level parallelism. In this case the most basic operations in each processor—addition, multiplication, loading registers—are executed in parallel. The goal is a new generation of microprocessors that will carry out these operations in parallel, even when given a program written with a single sequential processor in mind. More background on this subject is provided in the research news story by Freedman.

Vision is the “remote sensing” that some biological organisms and robots use to guide themselves through the world. What makes the job hard for robots is that the world is a cluttered place, riddled with obstacles and mirages. The goal of computer vision research is twofold: to understand the principles behind vision and to construct robots that can best make use of these principles. Aloimonos and Rosenfeld review past work in computer vision and recent efforts to implement it. Building on early efforts to analyze static two-dimensional images and controlled three-dimensional “blocks-worlds,” researchers are extending the theoretical foundations that they take on real-world scenes.

What would it be like if computers could be taught to understand the languages of humans, instead of the other way around? And what might we learn about human language as a result? Joshi discusses the field of natural language processing, an undertaking at the intersection of linguistics and computation. Much theoretical effort is devoted to grammars and parsers that specify and analyze natural languages. Another school of thought emphasizes the use of statistical information about real languages to guide the construction of useful systems. A practical application, multilingual translation by machine, has recently undergone a revival that will draw heavily on natural language processing.

The cutting edge in computer science has also found its way into the domain of molecular biology. Prediction of protein conformation from its amino acid sequence is a largely unsolved problem. A less explored but analogous task is the prediction of the twists and turns of RNA from its nucleotide sequence. Major et al. have tackled the RNA puzzle by viewing it as a constraint-satisfaction problem. By a combination of symbolic and numerical computation, the authors have accurately predicted three-dimensional RNA structures.

No brief collection of articles can hope to cover any field, especially one as vigorous as computer science. In this issue, entire branches of research in hardware and software have been unforgivably slighted; this will be rectified in issues to come. Still, these articles show that there is more to computer research than further decreases in the cost per megabyte, important as that may be. It is clear that in the future those megabytes will be put to novel and innovative purposes.—David Voss
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of information can be treated by minimization routines (23, 31, 33, 34), these data could be used more elegantly in the system we describe in this article.

REFERENCES AND NOTES
18. More information about MC-SYM can be obtained by sending an Email message to mcsym-request@ncbi.nlm.nihgov.

19. For the crystal structure of rRNA<sup>146</sup>, see D. Moras et al., Nature 228, 669 (1980). Data from the Brookhaven Protein Data Bank [F. C. Bernstein et al., J. Mol. Biol. 112, 535 (1977)].
25. Evaluated on a Sun SPARCstation 1+.
27. This value was obtained with N = 148, since 23 structures with major steric conflicts have been eliminated from the calculation; p has values between −1 and +1.
32. Although the rms deviation is an unbiased criterion of fit, it does not measure the relative position among atoms of the predicted structure.
35. We thank L. Jolicoeur for assistance in the early stages of this project. Supported by the Medical Research Council of Canada and the Fonds pour la formation de Chercheurs et l'Âide à la Recherche of Québec (FCAR); by Natural Sciences and Engineering Research Council of Canada postdoctoral fellowships (F.M. and M.T.); by a FCAR postdoctoral fellowship (F.M.) and a fellowship of the Canadian Institute for Advanced Research (R.C.).
11 February 1991; accepted 29 July 1991

"But we spend all our money creating toxic waste. We were hoping someone else would figure out how to detoxify it."

1260 SCIENCE, VOL. 253
rankled Shklovsky that his internal passport listed him as "Jew," not "Russian," especially since his education in the Soviet system had made him feel very much a full-fledged citizen of the country and he had served it well. He observes how many others suffered, sometimes much more seriously, from this pervasive anti-Semitism. Despite the extensive damage done to him by anti-Semitism, it is interesting that his condemnation of it, at least here, is limited—he seems to look upon anti-Semitism as one example among several of the weaknesses of some of the people in powerful positions in the Soviet Union.

Because of his contempt for pretense, Shklovsky loved to visit the West, where to him things were much closer to what they claimed to be. I remember a jolly walk with him on the first day of a meeting in Brighton, England. As though he had lived there all his life, he somehow knew how to lead us directly to his prime goal: a shoe store. He stood in front of the window and exalted at the shoes he saw; he knew they would be of a quality commensurate with their appearance, that he could buy them, and to him all was right with the world. In the book he describes a time when, by mistake, he was given a visa that allowed him to stay 12 days in Paris after a meeting. He had almost no money, but he was not about to be denied those days in Paris; here you can find a charming lesson on how to live in Paris on $1.40 a day and love every minute of it.

Nevertheless, Shklovsky's heart was deep in Russia. Although he knew he could have any number of glorious jobs in the West and could escape all the ill treatment he received in his own country, as far as we know he never even considered any of the many opportunities he had to leave Russia. In fact, if the subject was raised, he would not even talk about it. This was to the great benefit of the Soviet Union. He was an amazingly creative scientist. He started many important projects. He trained and motivated a large number of leading Soviet astronomers; indeed he worked hard to bring out the best in people. Recently we held a joint U.S.-U.S.S.R. scientific symposium that was attended by an impressive Soviet delegation. It was remarkable how many of those scientists had been students or colleagues of Shklovsky's. This book captures beautifully the essence of this unique and humane person, and how he came to be a person who could so influence his own and future eras.

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Homo habilis in Detail


Summer 1959 witnessed the discovery of what would prove to be two new, early species of extinct Hominidae from the oldest sediments exposed in the deepest reaches of Olduvai Gorge, northern Tanzania. The first, represented by a small jaw fragment with wisdom tooth (Olduvai Hominid 4), was utterly overshadowed by Mary Leakey's finding, shortly thereafter, of the marvelously preserved cranium (OH 5) that became the type of Australopithecus bosei (L. S. B. Leakey, 1959). However, beginning in late 1960 and repeatedly thereafter, further discoveries, largely from in situ excavations, eventuated in the recovery of additional hominid skull parts, some comparable to the initial fragment of 1959, sufficient to warrant recognition of a new species attributed to genus Homo, H. habilis (L. S. B. Leakey, P. V. Tobias, and J. R. Napier, 1964). In late 1968 the first largely complete, though much crushed, cranium with dentition (OH 24) was recovered, and subsequently (1971) it also was attributed to the species. In all as
many as two dozen individuals constitute the current Olduvai sample of this species, including (referred) postcranial elements and even diverse portions of a single individual’s skeleton (OH 62, found 1986).

These volumes, constituting the fourth in the Olduvai series and again lavishly produced by Cambridge University Press, document these discoveries, comment on the ensuing, often heated debate regarding their systematic status and phylogenetic significance, and consider the current status of *H. habilis*. Since its formal recognition as a new taxon, Phillip Tobias has in over 50 publications examined the nature, validity, and evolutionary significance of this ancient human species. These exquisitely detailed volumes are the culmination of his efforts and constitute the definitive treatment of the Olduvai fossil sample.

What sort of hominid was Olduvai’s *Homo habilis*? It was of diminutive stature (a female individual perhaps a meter in height), weighed some 25 to 35 kilograms, and had disproportionately long upper and shortened (upper) lower limbs. Sexual dimorphism was apparently moderate to substantial (broadly chimp-like). A partial femur (OH 62) reveals some primitive (*Australopithecus*-like) features; but the (attributed) subadult leg bones (OH 35) and partial subadult foot skeleton (OH 8) reveal an overall morphological pattern of human-like proportions and indicative of habitual upright stance and bipedal gait; the foot was essentially derived, not prehensile but plantigrade and propulsive, with adducted halluc, transverse and longitudinal arches, and close-packed tarsal elements, although lateral deviation of the heel was ill-expressed. Some bones of the manus (OH 7), mostly of a subadult and considered to represent the species because of their direct association with the type cranial parts, are more mosaic in morphological pattern: the digits exhibit strong flexor musculature, and the set of the thumb is indicative of some opposability if not full-power (“squeeze”) grip capability. Cranial capacity is significantly greater (by some 10 standard deviations) than in *A. africanus*, the *Australopithecus* species generally accorded the closest proximity to *Homo* ancestry, and the endocranial exhibits diverse, particularly transverse, expansion of fronto-parietal and temporal areas, altered sulcal and gyral dispositions, discernible expressions of two “language-related” (Broca’s, Wernicke’s) motor areas, and elaborated ramifications and anastomoses of the meningeal vascular system. The cranial base exhibits, relative to *A. africanus*, altered disposition of the atlanto-occipital joint, shortened anterior segment, and realignment and altered morphologies of aspects of the temporal bone, including the tempo-mandibular joint and the petrosal and mastoid areas. Calvarial vault bones are thinned and cranial tori are modest, though the supraorbital is salient; the brain case is elevated above the orbits and the frontal is domed; ectocranial superstructures are slight and realigned; and the occipital region reflects altered curvature, proportions, and attendant disposition of cranio-vertebral musculature. The facial skeleton is reduced (“gracilized”) overall, although alveolar prognathism is substantial; the palate is reduced; and the form of the mid-face, including the cheek region and nasal aperture, is altered. Mandibular robusticity is reduced, as are heights of the corpus and symphysis, and the interdental space is enhanced. Cheek-tooth size is relatively reduced, particularly posteriorly, and some anterior cheek teeth are relatively elongated with narrowed crowns and modified occlusal patterns; enamel is thinned and exhibits retarded attrition, and there is a distinctive twisted or helicoidal pattern of dental wear. Upper central incisors are large, the laterals are small, and the canines are generally high-crowned. Hence, overall the cranio-dental morphology diverges in consistent and important ways from the *A. africanus* condition, often considered the best (better) ancestral model for *Homo*. There are, however, some linkages postcranial...
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At Olduvai the H. habilis deme occurred (in discrete horizons, often with associated vertebrates and artifacts) in sediments of an intermittently flooded, saline–alkaline lake margin with interbedded tephra in Bed I and to just above Lemurta Aeolian-sorted tephra in (middle) Bed II. The time interval encompasses the eponymous Olduvai (N) geomagnetic subchron, here well dated radiometrically to 1.85 to 1.65 Ma, and the immediately reversed upper Matuyama (R) chron. Changes in environment, from more mesic (forested to wooded savanna) to more arid (substantial grassland) in Bed I and back to more mesic in (lower) Bed II, are consistently documented by sediments, isotopic geochemistry, palynology, and fossil vertebrates. Another hominid, A. boisei, is present, relatively uncommonly, penecontemporaneously within the basin during this interval (and later as well).

The other major occurrence of H. habilis, in eastern Africa, is in alluvio-deltaic and lake margin deposits of the Koobi Fora Formation, eastern Turkana basin (Kenya). There it is rather older, 1.9 to 1.88 Ma, although several specimens occur at 1.85 Ma; in the adjacent Omo basin (Ethiopia) it may extend still further back in time. Crania, mandibles, and dental elements, some assorted postcrania, and a fragmented skeleton (ER-3735) afford evidence critical toward fuller delineation of the species’ overall structure and morphology. In the earlier time range A. boisei is very rare (four cranial parts), subsequently (1.85 to 1.65 Ma) increasing in abundance remarkably (N = at least 34). Yet another hominid species, sometimes attributed to H. habilis (by various workers, including Tobias and previously myself) but now appropriately considered as a distinct taxon (Homo sp. nov. of B. A. Wood and others), occurs largely in the older time range. It differs significantly from H. habilis in cranio-gnathic-dental morphology, and evidently also in postcranial size and morphology, to judge from a diversity of such elements (unfortunately lacking direct skull-part associations). At the (presumed) end (1.85 Ma) of its documented span H. habilis is here penecontemporaneous with or succeeded by aforesaid H. sp. “aff. erectus” (= H. ergaster), as documented by at least seven cranio-gnathic specimens, between 1.85 and 1.65 Ma. Curiously, there is no concrete evidence for the latter species within the interval within which H. habilis occurs at Olduvai. The multiplicity of hom-
inid taxa, some persistent and some seemingly new appearances, documented in the reaches of the paleo-Turkana basin within this span of some 0.5 million years, has forced workers to reassess previous conceptions both of anagenesis and cladogenesis in respect to the origin (or origins) and phylogeny of genus Homo.

H. habilis is here considered one consequence (the other a “robust” Australopithecus lineage) of a major cladogenetic event, a moment of “explosive evolution,” around 2.5 to 2.3 Ma, broadly coincident with an episode of significant global climatic change inducing cooler, drier conditions and attendant environmental circumstances in equatorial and adjacent lower latitudes; this was an interval, also, when both extinctions and “vigorous autochthonous bio-evolution characterized Africa in the dying eons of the Pliocene.” The source (last common ancestor) of the splitting event is surmised to have been a “derived” morphotype of A. africanaus, that is, a descendant of A. africanaus and its forerunner, A. afarensis. The proleptic progenitor, postulated on the basis of a shared derived complex (synapomorphies) of cranial features found to co-occur in (subsequent) A. boisei/robustus and H. habilis, constitutes a projected link, although Tobias considers such a link might be represented even by the Taung child or be already in hand but insufficiently recognized among Omo-Shungura (Ethiopia) hominids of the appropriate geological age. H. habilis is recognized as a very early maker of stone tools to a set and consistent pattern, a species whose “cultural achievements . . . imply a high degree of intelligent activity” and a “lifestyle of much greater complexity,” such that “the transmission of such a culture would seem to have required speech and language,” an evolutionary novelty substantiated perhaps “by the appearance on the endocasts of evidence that the cerebral bases for spoken language were already present.” In sum, “Homo habilis” was enabled by its cerebral revolution to attain a new mode of evolution, as an articulate, language-bound, culture-dependent hominid.

The author’s perspective on the phylogenetic status of this species derives appropriately from overall morphological—structural—functional analysis, the species’ range in geologic time, an appraisal of the fossil record of other ancient Hominidae, and behavioral inferences from archaeological and vertebrate residues at some half-dozen Olduvai localities. Different perspectives lead other investigators to dissimilar interpretations. Such dissimilitude is reflected in a substantial and growing literature, a fair amount of which is not considered (cited) by the author (in part, at least, because these volumes were delivered to press almost five years prior to actual publication). 

Tobias’s monumental effort, essentially directed toward documenting the biological nature of an extinct human species at the unique Olduvai locality, provides as well a perspicacious, sweeping perspective relative to many aspects of hominid evolution. These volumes thus not only are a lastingly invaluable documentary reference but set forth diverse aspects of a research program that will engage students of the evolution of humankind for decades to come.

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