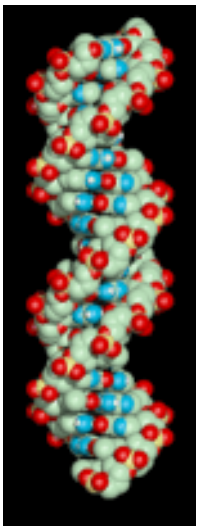
Molecular models of DNA

Molecular models of DNA structures are representations of the molecular geometry and topology of Deoxyribonucleic acid (DNA) molecules using one of several means, with the aim of simplifying and presenting the essential, physical and chemical, properties of DNA molecular structures either *in vivo* or *in vitro*. These representations include closely packed spheres (CPK models) made of plastic, metal wires for 'skeletal models', graphic computations and animations by computers, artistic rendering. Computer molecular models also allow animations and molecular dynamics simulations that are very important for understanding how DNA functions *in vivo*.



Spinning DNA generic model.

The more advanced, computer-based molecular models of DNA involve molecular dynamics simulations as well as quantum mechanical computations of vibro-rotations, delocalized molecular orbitals (MOs), electric dipole moments, hydrogen-bonding, and so on. **DNA molecular dynamics modeling** involves simulations of DNA molecular geometry and topology changes with time as a result of both intra- and inter- molecular interactions of DNA. Whereas molecular models of Deoxyribonucleic acid (DNA) molecules such as closely packed spheres (CPK models) made of plastic or metal wires for 'skeletal models' are useful representations of static DNA structures, their usefulness is very limited for representing complex DNA dynamics. Computer molecular modeling allows both animations and molecular dynamics simulations that are very important for understanding how DNA functions *in vivo*.

History

Double Helix Discovery

William Astbury

Oswald Avery

Francis Crick

Erwin Chargaff

Max Delbrück

Jerry Donohue

Rosalind Franklin

Raymond Gosling

Phoebus Levene

Linus Pauling

Sir John Randall

Erwin Schrödinger

Alex Stokes

James Watson

Maurice Wilkins

Herbert Wilson

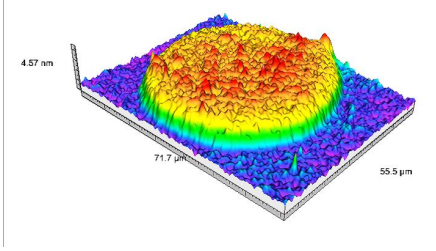
From the very early stages of structural studies of DNA by X-ray diffraction and biochemical means, molecular models such as the Watson-Crick double-helix model were successfully employed to solve the 'puzzle' of DNA structure, and also find how the latter relates to its key functions in living cells. The first high quality X-ray diffraction patterns of A-DNA were reported by Rosalind Franklin and Raymond Gosling in 1953[1] . The first calculations of the Fourier transform of an atomic helix were reported one year earlier by Cochran, Crick and Vand [2] , and were followed in 1953 by the computation of the Fourier transform of a coiled-coil by Crick[3] .

Structural information is generated from X-ray diffraction studies of oriented DNA fibers with the help of molecular models of DNA that are combined with crystallographic and mathematical analysis of the X-ray patterns.

The first reports of a double-helix molecular model of B-DNA structure were made by Watson and Crick in 1953[4] [5] . Last-but-not-least, Maurice F. Wilkins, A. Stokes and H.R. Wilson, reported the first X-ray patterns of *in vivo* B-DNA in partially oriented salmon sperm heads [6] . The development of the first correct double-helix molecular model of DNA by Crick and Watson may not have been possible without the biochemical evidence for the nucleotide base-pairing ([A---T]; [C---G]), or Chargaff's rules[7] [8] [9] [10] [11] [12] .Although such initial studies of DNA structures with the help of molecular models were essentially static, their consequences for explaining the *in vivo* functions of DNA were significant in the areas of protein biosynthesis and the quasi-universality of the genetic code. Epigenetic transformation studies of DNA *in vivo* were however much slower to develop in spite of their importance for embryology, morphogenesis and cancer research. Such chemical dynamics and biochemical reactions of DNA are much more complex than the molecular dynamics of DNA physical interactions with water, ions and proteins/enzymes in living cells.

Importance

An old standing dynamic problem is how DNA "self-replication" takes place in living cells that should involve transient uncoiling of supercoiled DNA fibers. Although DNA consists of relatively rigid, very large elongated biopolymer molecules called "fibers" or chains (that are made of repeating nucleotide units of four basic types, attached to deoxyribose and phosphate groups), its molecular structure *in vivo* undergoes dynamic configuration changes that involve dynamically attached water molecules and ions. Supercoiling, packing with histones in chromosome structures, and other such supramolecular aspects also involve *in vivo* DNA topology which is even more complex than DNA molecular geometry, thus turning molecular modeling of DNA into an especially challenging problem for both molecular biologists and biotechnologists. Like other large molecules and biopolymers, DNA often exists in multiple stable geometries (that is, it exhibits conformational isomerism) and configurational, quantum states which are close to each other in energy on the potential energy surface of the DNA molecule.

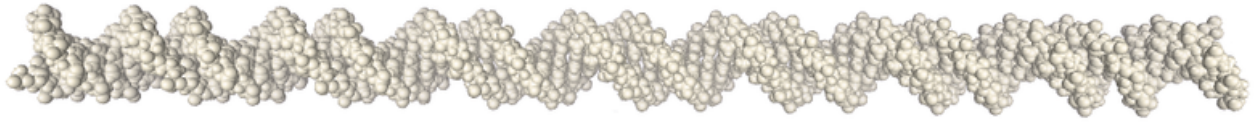


DNA computing biochip:3D

Such varying molecular geometries can also be computed, at least in principle, by employing *ab initio* quantum chemistry methods that can attain high accuracy for small molecules, although claims that acceptable accuracy can be also achieved for polynuclelotides, as well as DNA conformations, were recently made on the basis of VCD spectral data. Such quantum geometries define an important class of *ab initio* molecular models of DNA whose exploration has barely started especially in connection with results obtained by VCD in solutions. More detailed comparisons with such *ab initio* quantum computations are in principle obtainable through 2D-FT NMR spectroscopy and relaxation studies of polynucleotide solutions or specifically labeled DNA, as for example with deuterium labels.

In an interesting twist of roles, the DNA molecule itself was proposed to be utilized for quantum computing. Both DNA nanostructures as well as DNA 'computing' biochips have been built (see biochip image at left).

Examples of DNA molecular models



DNA Spacefilling molecular model

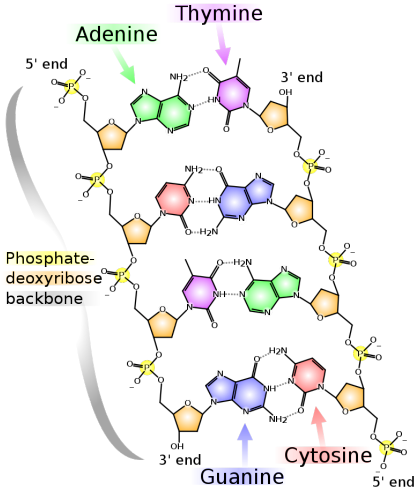


Fig.1. Chemical structure of DNA showing the base-pairing

The chemical structure of DNA sketched in Fig.1 is insufficient to understand the complexity of the 3D structures of DNA. On the other hand, animated molecular models allow one to visually explore the three-dimensional (3D) structure of DNA. Figure 2 shows the X-ray Patterns of A- and B- DNA configurations [13] that inspired the 3D double helix molecular models of DNA shown in Figures 3 and 4.

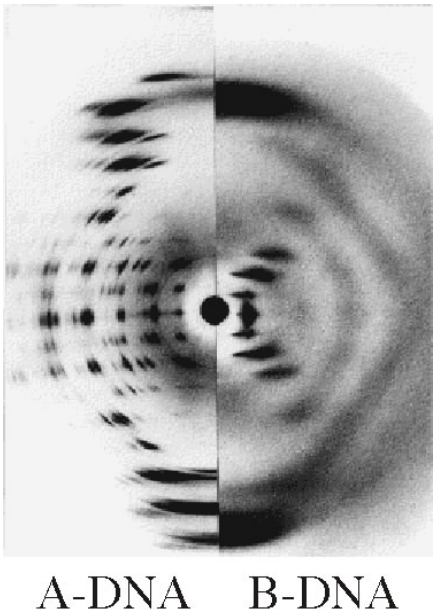


Fig.2. A- and B- DNA X-ray Patterns that served as a basis for the static 3D molecular models of DNA

The DNA model shown in Fig.3 is a space-filling, or CPK, model of the DNA double-helix. Animated molecular models allow one to visually explore the three-dimensional (3D) structure of DNA. One visualization of DNA model is a space-filling, or CPK, model.

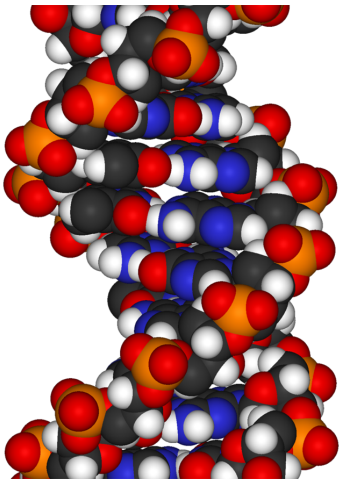


Fig.3. CPK, space-filling model of the DNA double-helix

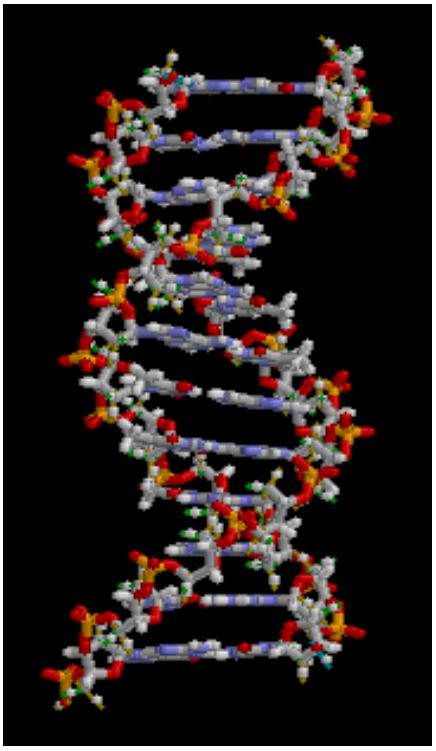


Fig.4. Animated 3D-wire model of A-DNA

Another type of molecular model is the wire, or skeletal, type shown in Fig.4.

The hydrogen bonding dynamics and proton exchange is very different by many orders of magnitude between the two systems of fully hydrated DNA and water molecules in ice shown in Fig.4. Thus, the DNA dynamics is complex, involving nanosecond and several tens of picosecond time scales, whereas that of liquid ice is on the picosecond time scale, and that of proton exchange in ice is on the millisecond time scale. A simple harmonic oscillator 'vibration' is only an oversimplified dynamic representation of the longitudinal vibrations of the DNA intertwined helices which were found to be anharmonic rather than harmonic as often assumed in quantum dynamic simulations of DNA.

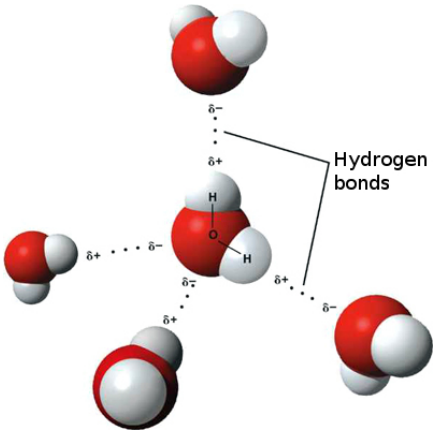


Fig.5. A 3D molecular model of H-bonds between water molecules in ice that are similar to those found in DNA

The proton exchange rates in DNA and attached proteins may vary from picosecond to nanosecond, minutes or years, depending on the exact locations of the exchanged protons in the large biopolymers. The next two DNA molecular models in Figures 6 and 7 of this section depict quadruplex DNA [14] that may be involved in certain cancers[15] [16] .

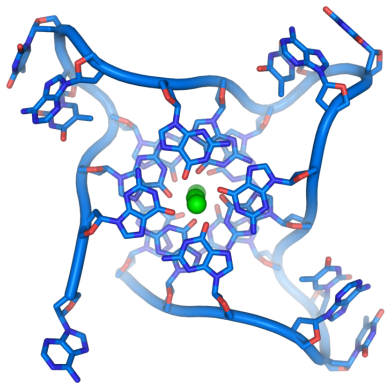


Fig.6. A hypothetical quadruplex of guanine-rich DNA structures that may be involved in cancers.

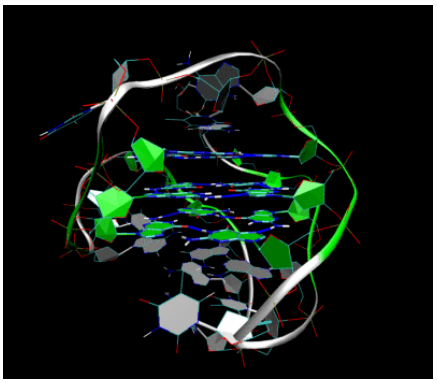
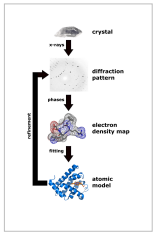


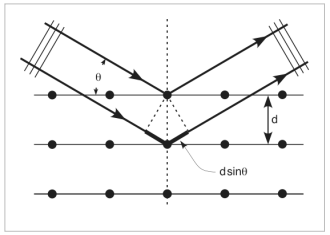
Fig.7. 3D Molecular Structure of the intramolecular human telomeric G-quadruplex in potassium solution.

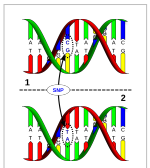
DNA structure determination using molecular modeling and DNA X-ray patterns

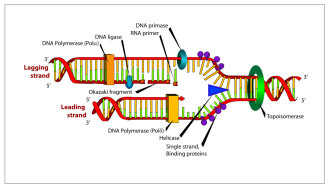
After DNA has been separated and purified by standard biochemical techniques one has a sample in a jar as shown in Fig.1 of **Gallery 1**. Figure 2 in **Gallery 1** specifies the main steps involved in generating structural information from X-ray diffraction studies of oriented DNA fibers that are drawn from the hydrated DNA sample (Fig.1) with the help of molecular models of DNA that are combined with crystallographic and mathematical analysis of the X-ray patterns. Figure 9 is an actual electron micrograph of a DNA fiber bundle, presumably of a single bacterial chromosome loop.

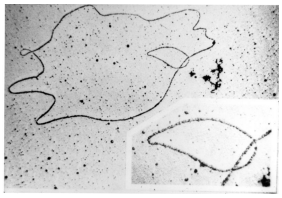
Gallery 1: Illustration of the molecular modeling and X-ray data collection steps involved in the determination of DNA molecular structures

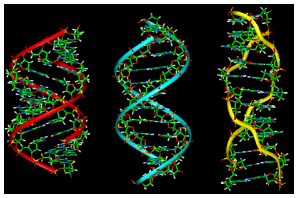


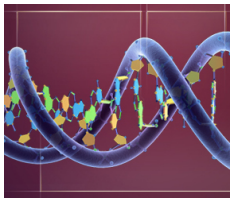


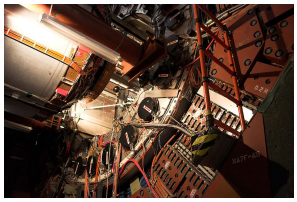






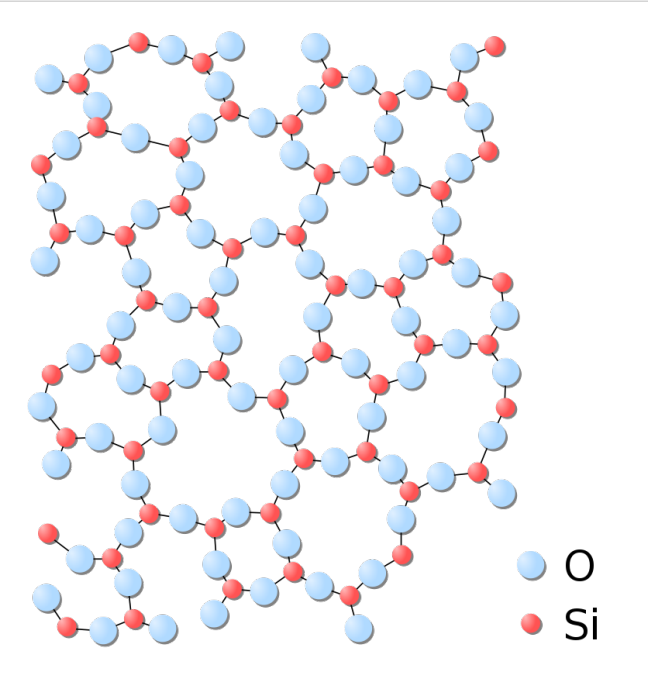






Paracrystalline lattice models of B-DNA structures

A paracrystalline lattice, or paracrystal, is a molecular or atomic lattice with significant amounts (e.g., larger than a few percent) of partial disordering of molecular arranegements. Limiting cases of the paracrystal model are nanostructures, such as glasses, liquids, etc., that may possess only local ordering and no global order. A simple example of a paracrystalline lattice is shown in the following figure for a silica glass:



Liquid crystals also have paracrystalline rather than crystalline structures.

Highly hydrated B-DNA occurs naturally in living cells in such a paracrystalline state, which is a dynamic one in spite of the relatively rigid DNA double-helix stabilized by parallel hydrogen bonds between the nucleotide base-pairs in the two complementary, helical DNA chains (see figures). For simplicity most DNA molecular models ommit both water and ions dynamically bound to B-DNA, and are thus less useful for understanding the dynamic behaviors of B-DNA *in vivo*. The physical and mathematical analysis of X-ray[17] [18] and spectroscopic data for paracrystalline B-DNA is therefore much more complicated than that of crystalline, A-DNA X-ray diffraction patterns. The paracrystal model is also important for DNA technological applications such as DNA nanotechnology. Novel techniques that combine X-ray diffraction of DNA with X-ray microscopy in hydrated living cells are now also being developed (see, for example, "Application of X-ray microscopy in the analysis of living hydrated cells" [19]).

Genomic and biotechnology applications of DNA molecular modeling

There are various uses of DNA molecular modeling in Genomics and Biotechnology research applications, from DNA repair to PCR and DNA nanostructures. Two-dimensional DNA junction arrays have been visualized by Atomic force microscopy.[20]

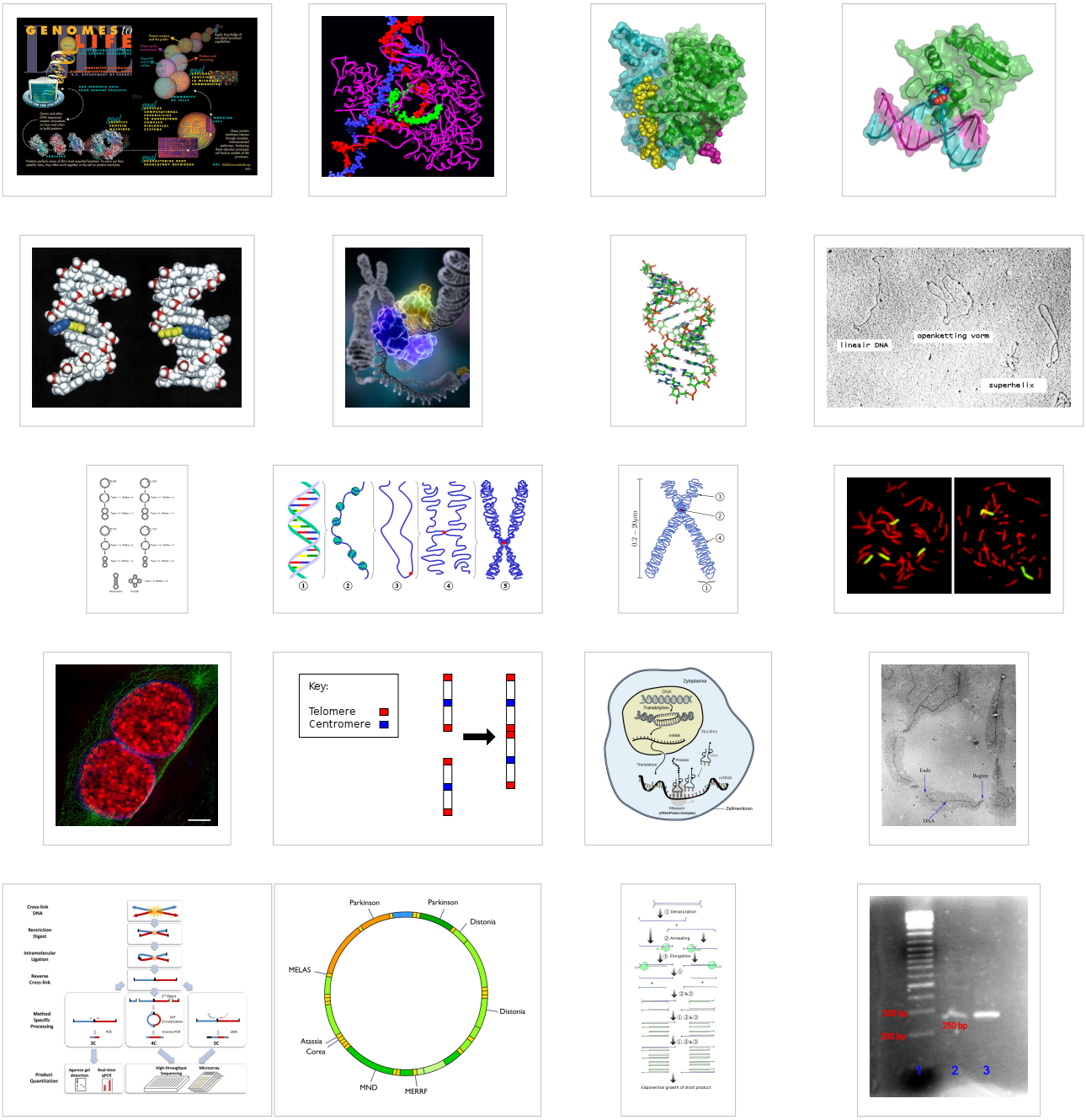
The following **Gallery 2** consists of images that illustrate various uses of DNA molecular modeling in Genomics and Biotechnology research applications from DNA repair to PCR and DNA nanostructures; each slide contains its own explanation and/or details. The first slide presents an overview of DNA applications, including DNA molecular models, with emphasis on Genomics and Biotechnology.

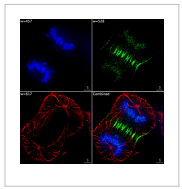
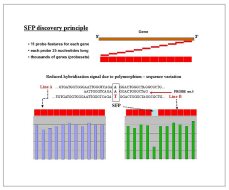
- The *first row*: Fig.2 shows a computer molecular model of RNA polymerase, followed in Figure 3 by that of an E. coli, bacterial DNA primase template suggesting very complex dynamics at the interfaces between the enzymes

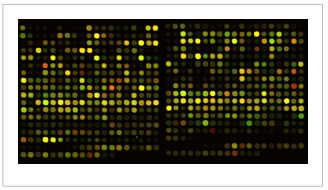
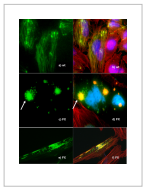
and the DNA template; the next Figures 4 and 5 illustrate in computed molecular models the mutagenic, chemical interaction of potent carcinogen molecules with DNA.

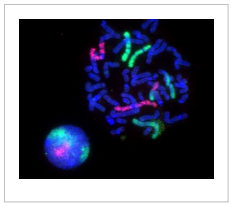
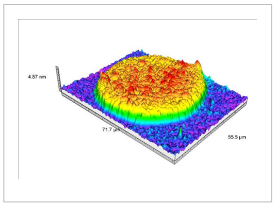
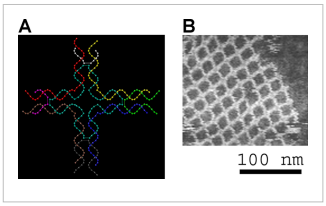
- The *last row* figures in **Gallery 2** present a DNA biochip and DNA nanostructures designed for DNA computing and other dynamic applications of DNA nanotechnology; last image in this row is of self-assembled DNA nanostructures. The DNA "tile" structure in this image consists of four branched junctions oriented at 90° angles. Each tile consists of nine DNA oligonucleotides as shown; such tiles serve as the primary "building block" for the assembly of the DNA nanogrids shown in the AFM micrograph.

Gallery 2: DNA molecular modeling applications in Genomics and Biotehnology



Quadruplex DNA [14] may be involved in certain cancers[21] [22] ; see also Figures 6 and 7 in the section on 3D molecular models.

See also

- DNA
- DNA structure
- G-quadruplex
- Crystallography
- Crystal lattices
- X-ray scattering
- Sir Lawrence Bragg, FRS
- List of nucleic acid simulation software
- Neutron scattering
- X-ray microscopy
- Sirius visualization software
- QMC@Home
- 2D-FT NMRI and Spectroscopy
- FT-NMR[23] [24]
- NMR microscopy[25]
- Microwave spectroscopy
- Vibrational circular dichroism (VCD)
- FT-IR
- FT-NIR[26] [27] [28]
- Spectral, Hyperspectral, and Chemical imaging)[29] [30] [31] [26] [27] [32] [33] .
- Raman spectroscopy/microscopy[34] and CARS[35] .
- Fluorescence correlation spectroscopy[36] [37] [38] [27] [39] [40] [41] [26] ,
- Fluorescence cross-correlation spectroscopy and FRET[42] [43] [44] .
- Confocal microscopy[36]

Further reading

- *Applications of Novel Techniques to Health Foods, Medical and Agricultural Biotechnology*.(June 2004) I. C. Baianu, P. R. Lozano, V. I. Prisecaru and H. C. Lin., q-bio/0406047.
- F. Bessel, *Untersuchung des Theils der planetarischen Störungen*, Berlin Abhandlungen (1824), article 14.
- Sir Lawrence Bragg, FRS. *The Crystalline State, A General survey.* London: G. Bells and Sons, Ltd., vols. 1 and 2., 1966., 2024 pages.
- Cantor, C. R. and Schimmel, P.R. *Biophysical Chemistry, Parts I and II*., San Franscisco: W.H. Freeman and Co. 1980. 1,800 pages.
- Voet, D. and J.G. Voet. *Biochemistry*, 2nd Edn., New York, Toronto, Singapore: John Wiley & Sons, Inc., 1995, ISBN 0-471-58651-X., 1361 pages.
- Watson, G. N. *A Treatise on the Theory of Bessel Functions*., (1995) Cambridge University Press. ISBN 0-521-48391-3.
- Watson, James D. *Molecular Biology of the Gene.* New York and Amsterdam: W.A. Benjamin, Inc. 1965., 494 pages.
- Wentworth, W.E. *Physical Chemistry. A short course.*, Malden (Mass.): Blackwell Science, Inc. 2000.
- Herbert R. Wilson, FRS. *Diffraction of X-rays by proteins, Nucleic Acids and Viruses*., London: Edward Arnold (Publishers) Ltd. 1966.
- Kurt Wuthrich. *NMR of Proteins and Nucleic Acids.*, New York, Brisbane,Chicester, Toronto, Singapore: J. Wiley & Sons. 1986., 292 pages.
- Robinson, Bruche H.; Seeman, Nadrian C. (August 1987). "The Design of a Biochip: A Self-Assembling Molecular-Scale Memory Device". *Protein Engineering* **1** (4): 295–300. ISSN 0269-2139. Link [45]
- Rothemund, Paul W. K.; Ekani-Nkodo, Axel; Papadakis, Nick; Kumar, Ashish; Fygenson, Deborah Kuchnir & Winfree, Erik (22 December 2004). "Design and Characterization of Programmable DNA Nanotubes". *Journal of the American Chemical Society* **126** (50): 16344–16352. doi:10.1021/ja044319l. ISSN 0002-7863.
- Keren, K.; Kinneret Keren, Rotem S. Berman, Evgeny Buchstab, Uri Sivan, Erez Braun (November 2003). "DNA-Templated Carbon Nanotube Field-Effect Transistor" [46]. *Science* **302** (6549): 1380–1382. doi:10.1126/science.1091022. ISSN 1095-9203.
- Zheng, Jiwen; Constantinou, Pamela E.; Micheel, Christine; Alivisatos, A. Paul; Kiehl, Richard A. & Seeman Nadrian C. (2006). "2D Nanoparticle Arrays Show the Organizational Power of Robust DNA Motifs". *Nano Letters* **6**: 1502–1504. doi:10.1021/nl060994c. ISSN 1530-6984.
- Cohen, Justin D.; Sadowski, John P.; Dervan, Peter B. (2007). "Addressing Single Molecules on DNA Nanostructures". *Angewandte Chemie* **46** (42): 7956–7959. doi:10.1002/anie.200702767. ISSN 0570-0833.
- Constantinou, Pamela E.; Wang, Tong; Kopatsch, Jens; Israel, Lisa B.; Zhang, Xiaoping; Ding, Baoquan; Sherman, William B.; Wang, Xing; Zheng, Jianping; Sha, Ruojie & Seeman, Nadrian C. (2006). "Double cohesion in structural DNA nanotechnology". *Organic and Biomolecular Chemistry* **4**: 3414–3419. doi:10.1039/b605212f.
- Hallin PF, David Ussery D (2004). "CBS Genome Atlas Database: A dynamic storage for bioinformatic results and DNA sequence data". *Bioinformatics* **20**: 3682–3686.
- Zhang CT, Zhang R, Ou HY (2003). "The Z curve database: a graphic representation of genome sequences". Bioinformatics 19 (5): 593-599. doi:10.1093/bioinformatics/btg041

External links

- DNA the Double Helix Game [47] From the official Nobel Prize web site
- MDDNA: Structural Bioinformatics of DNA [48]
- Double Helix 1953–2003 [49] National Centre for Biotechnology Education
- DNAlive: a web interface to compute DNA physical properties [50]. Also allows cross-linking of the results with the UCSC Genome browser and DNA dynamics.
- DiProDB: Dinucleotide Property Database [51]. The database is designed to collect and analyse thermodynamic, structural and other dinucleotide properties.
- Further details of mathematical and molecular analysis of DNA structure based on X-ray data [52]
- Bessel functions corresponding to Fourier transforms of atomic or molecular helices. [53]
- Application of X-ray microscopy in analysis of living hydrated cells [19]
- overview of STM/AFM/SNOM principles with educative videos [54]

Databases for DNA molecular models and sequences

X-ray diffraction

- NDB ID: UD0017 Database [14]
- X-ray Atlas -database [55]
- PDB files of coordinates for nucleic acid structures from X-ray diffraction by NA (incl. DNA) crystals [56]
- Structure factors dowloadable files in CIF format [57]

Neutron scattering

- ISIS neutron source: ISIS pulsed neutron source:A world centre for science with neutrons & muons at Harwell, near Oxford, UK. [58]

X-ray microscopy

- Application of X-ray microscopy in the analysis of living hydrated cells [19]

Electron microscopy

- DNA under electron microscope [59]

NMR databases

- NMR Atlas--database [60]
- mmcif downloadable coordinate files of nucleic acids in solution from 2D-FT NMR data [61]
- NMR constraints files for NAs in PDB format [62]

Genomic and structural databases

- CBS Genome Atlas Database [63] — contains examples of base skews.
- The Z curve database of genomes — a 3-dimensional visualization and analysis tool of genomes [64].
- DNA and other nucleic acids' molecular models: Coordinate files of nucleic acids molecular structure models in PDB and CIF formats [65]

Atomic force microscopy

- How SPM Works [66]
- SPM Image Gallery - AFM STM SEM MFM NSOM and more. [67]

References

[1] Franklin, R.E. and Gosling, R.G. recd.6 March 1953. Acta Cryst. (1953). 6, 673 The Structure of Sodium Thymonucleate Fibres I. The Influence of Water Content Acta Cryst. (1953). and 6, 678 The Structure of Sodium Thymonucleate Fibres II. The Cylindrically Symmetrical Patterson Function.

[2] Cochran, W., Crick, F.H.C. and Vand V. 1952. The Structure of Synthetic Polypeptides. 1. The Transform of Atoms on a Helix. Acta Cryst. 5(5):581-586.

[3] Crick, F.H.C. 1953a. The Fourier Transform of a Coiled-Coil., Acta Crystallographica 6(8-9):685-689.

[4] Watson, James D. and Francis H.C. Crick. A structure for Deoxyribose Nucleic Acid (http://www.nature.com/nature/dna50/watsoncrick.pdf) (PDF). *Nature* 171, 737–738, 25 April 1953.

[5] Watson, J.D; Crick F.H.C. 1953b. The Structure of DNA., Cold Spring Harbor Symposia on Qunatitative Biology 18:123-131.

[6] Wilkins M.H.F., A.R. Stokes A.R. & Wilson, H.R. (1953). "Molecular Structure of Deoxypentose Nucleic Acids" (http://www.nature.com/nature/dna50/wilkins.pdf) (PDF). *Nature* **171** (4356): 738–740. doi:10.1038/171738a0. PMID 13054693. .

[7] Elson D, Chargaff E (1952). "On the deoxyribonucleic acid content of sea urchin gametes". *Experientia* **8** (4): 143–145.

[8] Chargaff E, Lipshitz R, Green C (1952). "Composition of the deoxypentose nucleic acids of four genera of sea-urchin". *J Biol Chem* **195** (1): 155–160. PMID 14938364.

[9] Chargaff E, Lipshitz R, Green C, Hodes ME (1951). "The composition of the deoxyribonucleic acid of salmon sperm". *J Biol Chem* **192** (1): 223–230. PMID 14917668.

[10] Chargaff E (1951). "Some recent studies on the composition and structure of nucleic acids". *J Cell Physiol Suppl* **38** (Suppl).

[11] Magasanik B, Vischer E, Doniger R, Elson D, Chargaff E (1950). "The separation and estimation of ribonucleotides in minute quantities". *J Biol Chem* **186** (1): 37–50. PMID 14778802.

[12] Chargaff E (1950). "Chemical specificity of nucleic acids and mechanism of their enzymatic degradation". *Experientia* **6** (6): 201–209.

[13] http://commons.wikimedia.org/wiki/Category:DNA

[14] http://ndbserver.rutgers.edu/atlas/xray/structures/U/ud0017/ud0017.html

[15] http://www.phy.cam.ac.uk/research/bss/molbiophysics.php

[16] http://planetphysics.org/encyclopedia/TheoreticalBiophysics.html

[17] Hosemann R., Bagchi R.N., *Direct analysis of diffraction by matter*, North-Holland Publs., Amsterdam – New York, 1962.

[18] Baianu, I.C. (1978). "X-ray scattering by partially disordered membrane systems.". *Acta Cryst.,* **A34** (5): 751–753. doi:10.1107/S0567739478001540.

[19] http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=pubmed&dopt=Abstract&list_uids=12379938

[20] Mao, Chengde; Sun, Weiqiong & Seeman, Nadrian C. (16 June 1999). "Designed Two-Dimensional DNA Holliday Junction Arrays Visualized by Atomic Force Microscopy". *Journal of the American Chemical Society* **121** (23): 5437–5443. doi:10.1021/ja9900398. ISSN 0002-7863.

[21] http://www.phy.cam.ac.uk/research/bss/molbiophysics.php

[22] http://planetphysics.org/encyclopedia/TheoreticalBiophysics.html

[23] (http://www.jonathanpmiller.com/Karplus.html)- obtaining dihedral angles from ^{3}J coupling constants

[24] (http://www.spectroscopynow.com/FCKeditor/UserFiles/File/specNOW/HTML files/General_Karplus_Calculator.htm) Another Javascript-like NMR coupling constant to dihedral

[25] Lee, S. C. et al., (2001). One Micrometer Resolution NMR Microscopy. *J. Magn. Res*., **150**: 207-213.

[26] Near Infrared Microspectroscopy, Fluorescence Microspectroscopy,Infrared Chemical Imaging and High Resolution Nuclear Magnetic Resonance Analysis of Soybean Seeds, Somatic Embryos and Single Cells., Baianu, I.C. et al. 2004., In *Oil Extraction and Analysis.*, D. Luthria, Editor pp.241-273, AOCS Press., Champaign, IL.

[27] Single Cancer Cell Detection by Near Infrared Microspectroscopy, Infrared Chemical Imaging and Fluorescence Microspectroscopy.2004.I. C. Baianu, D. Costescu, N. E. Hofmann, S. S. Korban and et al., q-bio/0407006 (July 2004) (http://arxiv.org/abs/q-bio/0407006)

[28] Raghavachari, R., Editor. 2001. *Near-Infrared Applications in Biotechnology*, Marcel-Dekker, New York, NY.

[29] http://www.imaging.net/chemical-imaging/Chemical imaging

[30] http://www.malvern.com/LabEng/products/sdi/bibliography/sdi_bibliography.htm E. N. Lewis, E. Lee and L. H. Kidder, Combining Imaging and Spectroscopy: Solving Problems with Near-Infrared Chemical Imaging. Microscopy Today, Volume 12, No. 6, 11/2004.

[31] D.S. Mantus and G. H. Morrison. 1991. Chemical imaging in biology and medicine using ion microscopy., *Microchimica Acta*, **104**, (1-6) January 1991, doi: 10.1007/BF01245536

[32] J. Dubois, G. Sando, E. N. Lewis, Near-Infrared Chemical Imaging, A Valuable Tool for the Pharmaceutical Industry, G.I.T. Laboratory Journal Europe, No.1-2, 2007.

[33] Applications of Novel Techniques to Health Foods, Medical and Agricultural Biotechnology.(June 2004).,I. C. Baianu, P. R. Lozano, V. I. Prisecaru and H. C. Lin q-bio/0406047 (http://arxiv.org/abs/q-bio/0406047)

[34] Chemical Imaging Without Dyeing (http://witec.de/en/download/Raman/ImagingMicroscopy04.pdf)

[35] C.L. Evans and X.S. Xie.2008. Coherent Anti-Stokes Raman Scattering Microscopy: Chemical Imaging for Biology and Medicine., doi:10.1146/annurev.anchem.1.031207.112754 *Annual Review of Analytical Chemistry*, **1**: 883-909.

[36] Eigen, M., Rigler, R. Sorting single molecules: application to diagnostics and evolutionary biotechnology,(1994) *Proc. Natl. Acad. Sci. USA*, 91,5740-5747.

[37] Rigler, M. Fluorescence correlations, single molecule detection and large number screening. Applications in biotechnology,(1995) J. Biotechnol., 41,177-186.
[38] Rigler R. and Widengren J. (1990). Ultrasensitive detection of single molecules by fluorescence correlation spectroscopy, *BioScience* (Ed. Klinge & Owman) p.180.
[39] Oehlenschläger F., Schwille P. and Eigen M. (1996). Detection of HIV-1 RNA by nucleic acid sequence-based amplification combined with fluorescence correlation spectroscopy, *Proc. Natl. Acad. Sci. USA* **93**:1281.
[40] Bagatolli, L.A., and Gratton, E. (2000). Two-photon fluorescence microscopy of coexisting lipid domains in giant unilamellar vesicles of binary phospholipid mixtures. Biophys J., 78:290-305.
[41] Schwille, P., Haupts, U., Maiti, S., and Webb. W.(1999). Molecular dynamics in living cells observed by fluorescence correlation spectroscopy with one- and two-photon excitation. Biophysical Journal, 77(10):2251-2265.
[42] FRET description (http://dwb.unl.edu/Teacher/NSF/C08/C08Links/pps99.cryst.bbk.ac.uk/projects/gmocz/fret.htm)
[43] doi:10.1016/S0959-440X(00)00190-1 (http://dx.doi.org/10.1016/S0959-440X(00)00190-1)Recent advances in FRET: distance determination in protein–DNA complexes. *Current Opinion in Structural Biology* **2001**, *11(2)*, 201-207
[44] http://www.fretimaging.org/mcnamaraintro.html FRET imaging introduction
[45] http://peds.oxfordjournals.org/cgi/content/abstract/1/4/295
[46] http://www.sciencemag.org/cgi/content/abstract/sci;302/5649/1380
[47] http://nobelprize.org/educational_games/medicine/dna_double_helix/
[48] http://humphry.chem.wesleyan.edu:8080/MDDNA/
[49] http://www.ncbe.reading.ac.uk/DNA50/
[50] http://mmb.pcb.ub.es/DNAlive
[51] http://diprodb.fli-leibniz.de
[52] http://planetphysics.org/encyclopedia/BesselFunctionsApplicationsToDiffractionByHelicalStructures.html
[53] http://planetphysics.org/?op=getobj&from=objects&name=BesselFunctionsAndTheirApplicationsToDiffractionByHelicalStructures
[54] http://www.ntmdt.ru/SPM-Techniques/Principles/
[55] http://ndbserver.rutgers.edu/atlas/xray/index.html
[56] http://ndbserver.rutgers.edu/ftp/NDB/coordinates/na-biol/
[57] http://ndbserver.rutgers.edu/ftp/NDB/structure-factors/
[58] http://www.isis.rl.ac.uk/
[59] http://www.fidelitysystems.com/Unlinked_DNA.html
[60] http://ndbserver.rutgers.edu/atlas/nmr/index.html
[61] http://ndbserver.rutgers.edu/ftp/NDB/coordinates/na-nmr-mmcif/
[62] http://ndbserver.rutgers.edu/ftp/NDB/nmr-restraints/
[63] http://www.cbs.dtu.dk/services/GenomeAtlas/
[64] http://tubic.tju.edu.cn/zcurve/
[65] http://ndbserver.rutgers.edu/ftp/NDB/models/
[66] http://www.parkafm.com/New_html/resources/01general.php
[67] http://www.rhk-tech.com/results/showcase.php

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