The Practice of Informatics

Review ■

The World Wide Web: A Review of an Emerging Internet-based Technology for the Distribution of Biomedical Information

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Abstract The Internet is rapidly evolving from a resource used primarily by the research community to a true global information network offering a wide range of databases and services. This evolution presents many opportunities for improved access to biomedical information, but Internet-based resources have often been difficult for the non-expert to develop and use. The World Wide Web (WWW) supports an inexpensive, easy-to-use, cross-platform, graphic interface to the Internet that may radically alter the way we retrieve and disseminate medical data. This paper summarizes the Internet and hypertext origins of the WWW, reviews WWW-specific technologies, and describes current and future applications of this technology in medicine and medical informatics. The paper also includes an appendix of useful biomedical WWW servers.

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The Internet is rapidly evolving from a resource used primarily by the research community to a true global information network offering, in many cases, unrestricted access to a wide range of databases and services. This rapid growth in Internet use is being driven by a number of factors, including increasing "computer literacy," availability of affordable personal computers (PCs), and the development of easy-to-use communication software. Media coverage of the Internet has also resulted in more widespread awareness of how this global data network can enhance business, science, and education. In turn, this awareness has produced a significant demand for affordable commercial services providing Internet access to those outside of the scientific and educational communities.

One of the most significant developments driving this growth has been the emergence of the World Wide Web (WWW) as a technology for accessing the vast array of resources available on the Internet. The WWW provides an easy-to-use, inexpensive, cross-platform, graphic interface that allows even a casual user to successfully navigate the complex web of linked computer systems that is the Internet. The impact of WWW technology on biomedicine may be significant. The ease of creating and accessing Internet-based WWW servers combined with the platform-indepen-

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dent capabilities of this technology will likely result in the widespread availability of clinical, research, and educational resources on the Internet. This paper provides an overview of the history and technology of the WWW, describes a number of existing biomedical WWW servers, and discusses future medical applications of this important technology. In addition, we have included an appendix containing pointers to a variety of useful WWW resources and sites.

The Internet

The Internet, as we know it, was initially conceived by Paul Baran, an employee of the Rand Corporation. First published in a series of Rand reports in the early 1960s, Baran's ideas would become realized with the creation of the Advanced Research Projects Agency Network (ARPANET) in 1968.[18] The introduction of the Transmission Control Protocol/Internet Protocol (TCP/IP) in the early 1970s allowed for interoperability between heterogeneous computer systems, end-to-end communication across a multitude of diverse networks, and robust, automatic handling of data link failures.

The original aim of the ARPANET was to provide remote access to distant computers, remote file sharing, and the expansion of computer science research through resource sharing. The ARPANET was dissolved in 1990, having evolved into the Internet, a collection of interconnected networks that span the globe. The Internet has become the fastest-growing electronic network in the world. Current host growth rates are estimated at 10% per month, with network traffic doubling annually.[67] TCP/IP, the principal communications protocol of the Internet, has been widely accepted. Until recently, the U.S. portion of the Internet was funded, in part, by the federal government. The National Information Infrastructure (NII) initiative sponsored by the federal government has redefined this funding model and replaced it with private-sector investment and network management.

A significant recent development has been the widespread adoption of the WWW,[68] and, especially, a number of easy-to-use browsers, which offers a graphic user interface to the Internet. This paper focuses on the WWW and its potential in clinical information dissemination and retrieval. For a more general treatment of the Internet and its application in medicine, the reader may wish to consult a number of recent papers on the subject.[34,82] WWW technology, based in part on the hypertext concept, may be a significant catalyst in the transformation of the Internet from a research tool to a true global information network.

Hypertext: A Brief Introduction

The WWW is essentially a network-based, distributed hypertext system. Initially envisioned by Bush,[1] further described by Engelbart,[2] and defined by Nelson,[4] the conceptual model underlying computer-mediated hypertext in modern information systems is a simple one. Links to component objects or nodes (e.g., text, images, sound) are embedded in a given document or set of documents. These nodes may be linked to associated nodes to form a database by way of a set of links. The logical extension of this model is that of a "meta-document" that would essentially be a hypermedia database of hypertext documents. This model allows the user to easily navigate an arbitrary set of links between nodes in a document or database based on the user's information needs rather than the fixed data linkages defined in traditional information retrieval systems.

In a definitive article on the subject, Conklin suggests the following four broad applications for computer-based hypertext systems,[10] and potentially WWW, which are relevant to medical practice and medical informatics:

- *macro literary stystems*: systems and technology that support large on-line libraries with computer mediated interdocument links (for example, network-oriented publishing, reading, criticism, and collaboration in document creation).
- *problem exploration systems*: tools to support early unstructured thinking on a given problem (for example, early authoring, outlining, problem solving, programming, and design).
- *structured browsing systems*: small-scale teaching, reference, and public information systems similar in design and function to macro literary systems. In these systems, ease of use is a critical design component.
- *general hypertext systems*: general-purpose systems for reading, writing, collaboration, etc., designed to allow experimentation with a range of hypertext applications.

Macro literary systems were among the first attempts at computer-based hypertext systems. Bush's visionary concept of the "memex,"[1] a machine/model for browsing and note creation in an environment of extensive on-line text and graphics, was the underlying impetus for these systems.

Among the major efforts in this arena include the work of Engelbart, the creator of the mouse, and his NLS/AUGMENT system[7]; Nelson and the Xanadu project[3]; and Trig,[6] credited with having written the first PhD thesis on hypertext, and his TEXTNET system in which documents were organized as "primitive pieces of text connected with typed links to form a network similar in many ways to a semantic net."

Problem exploration systems are interactive systems designed to aid in the organization, filtering, and presentation of ideas for problem solving. The Issue-Based Information System developed by Rittel and Webber[5] and *structured browsing systems* such as ZOG[8] and Knowledge Systems' Knowledge Management System (KMS)[9] developed by McCraken and Akscyn at Carnegie Mellon University were among the earliest and best-known hypertext implementations of this type.

Xerox PARC, with their NoteCards[11] product, is credited with the earliest commercial implementation of a *general hypertext system*. NoteCards was designed as an information analyst's support tool. The aim of this research effort was the development of a technology that would facilitate the formation and expression of conceptual models and analyses. Many of the ideas behind the implementation of NoteCards have been used in later hypertext software packages.

Since Bush's introduction of the conceptual foundations of hypertext, technology and implementation, in his landmark 1945 article, "As We May Think,"[1] there has been increasing interest in both the implementation and the practical application of hypertext. While the conceptual model supporting hypertext has been extant for some time, Conklin suggests that the recent explosion of interest in hypertext has been fueled by the general acceptance of the computer, especially the PC, as an idea-, word-, and symbol-processing tool as well as an interpersonal communication device.[10]

As an information technology, hypertext is a curious hybrid that traverses a number of traditional computer science boundaries. First, hypertext is a database methodology that offers a new and different way of accessing data that is a radical departure from more traditional approaches. In addition, hypertext is a representation scheme, similar in form to a semantic network combining informally arranged textual material with formal, mechanized operations and processes. Hypertext is also an interface modality featuring linked objects (e.g., icons, images, and text) that are often embedded in a given document by the user. The merging of these ideas with wide-area networking technology is the basis for development of the WWW.

The World Wide Web

In its mature form, Nelson saw the Xanadu project as a global literary system, with its vast "docuverse," as the key to widely distributed access to and sharing of information. In many respects, Nelson's vision may be close to realization in the maturation of the hypertext model within the emerging WWW.

The WWW project was initiated in 1989, as an in-house personal hypertext information system, at the European Particle Physics Laboratory (CERN) in Geneva, Switzerland. According to Berners-Lee, the principal architect, and colleagues, the "World Wide Web was developed to be a pool of human knowledge, which would allow collaborators in remote sites to share their ideas and all aspects of a common project."[19]

Much of the present development of the WWW project and related technology is actively supported by the World Wide Web Consortium (W3C) and the Internet Engineering Task Force (IETF). The W3C, formed by CERN, the French National Institute for Research in Computers and Automation (INRIA), and the Massachusetts Institute of Technology (MIT), exists to promote the development of common standards for the WWW and serve as a repository of related data, information, and software applications.[63] The IETF is a forum for researchers, network designers, and vendors to identify and propose solutions to operational or technical problems related to the Internet.[35]

The WWW initiative was developed with a client–server-distributed computing architecture as its delivery mechanism. The assumptions of the project were:

1. The idea of a "boundless" information space in which all items have a referent that aids directly in the item's retrieval.
2. An addressing system, the Uniform Resource Identifier (URI), created and implemented to make this space possible regardless of the underlying protocol necessary for transport or communications.
3. A network communications protocol, the Hypertext Transfer Protocol (HTTP), to provide network performance and services for WWW servers.
4. The Hypertext Markup Language (HTML), which would be understood by every WWW client and used to transmit text, menus, and on-line help information.

Table 1 ■

Some Common Default Values and Formats for Each Uniform Resource Locator (URL) Scheme

Protocol*	URL Format
FTP	ftp://user:password@host:port/path
HTTP	http://host:port/path?searchpart
Gopher	gopher://host:port.path
Telnet	telnet://user:password@host:port
Mailto	user_name@host
File	file://host/path

*FTP = File Transfer Protocol; HTTP = Hypertext Transfer Protocol.

5. A collection of documents and an associated body of data, available on the Internet, that would employ these elements.

Uniform Resource Identifier

The idea of the WWW is predicated on the concept of a "boundless" information space populated by a collection of data objects linked via a communication protocol. The URI, as defined in the IETF specification document RFC-1630, is a convention that is used to identify the "registered name spaces and addresses" of a given resource object (documents, images, etc.) on the Web.

At present, two forms of URIs exist: the Uniform Resource Locator (URL) and the Uniform Resource Name (URN). The more commonly used URL is a form of URI that, through the use of an addressing protocol, provides an access method for retrieving a given resource on the WWW. For example, one could use the File Transfer Protocol (FTP) to retrieve a file from a WWW server. The URN is an evolving schema for naming resources that may be used to map a specific name to one or more resources.[62]

URLs have been in use on the WWW since 1990 and went on the Internet standards track (RFC 1738) in 1994.[40] The syntax of the URL follows the Common Internet Scheme Syntax (CISS) and is as follows: <access protocol>://<host>/<path>. For example, the URL for the home page of the University of Pittsburgh Section of Medical Informatics WWW server is: *http://www.smi.med.pitt.edu/welcome.html*. In this case, *http* is the access protocol, *www.smi.med.pitt.edu* refers to the host, and *welcome.html* refers to the host directory path to the servers home page.

In its present form, the URL provides the actual location of a given link. Every WWW resource page has a unique URL. As can be seen in Table 1, URLs support protocols other than HTTP on the WWW (e.g., FTP, Gopher, HTTP). The "mailto" URL indicates that an electronic mail message is to be sent to a given electronic mail address. The mailto URL is one of the URL schemes that does not use the CISS format. It is important to note, that, at present, a number of WWW browsers (such as Mosaic) do not support the mailto URL.

Hypertext Transfer Protocol

HTTP is the client–server communication protocol unique to the WWW and was designed to be the communication vehicle for the transfer of information between the WWW client and the server.[64] HTTP is a simple request–response protocol allowing for communication between the WWW client and a given HTTP server. One HTTP server can serve information to a multitude of clients. HTTP provides the user with an efficient means to traverse the WWW and retrieve data objects or items relatively quickly and from disparate servers.

HTTP 0.9 was initially implemented in 1991. HTTP/1.0 is in the draft stage as an Internet standard. All HTTP messages incorporate the Multipurpose Internet Mail Extension (MIME) standard for the identification and transfer of data in a variety of formats as defined in the RFC 1341.[37] Plain-text, hypertext, image, audio, and video data can be transferred using this protocol.

HTTP is a stateless protocol that limits a given client to one request per connection. In the stateless model, a client connects to the server, makes a request, receives a response, and disconnects. There is no record of multiple transactions inherent in the protocol. An analogous view of this model would be the contrast between sending a letter and making a telephone call. In this instance, the telephone call would be connection-oriented, requiring a physical "connection" (i.e., an open line) between the caller and the called party. However, in the case of a letter, once it is mailed, the connection is complete. The stateless protocol promotes efficient use of server resources. In this model, the server uses its resources for a limited time and only when requested.

Hypertext Markup Language

HTML is a simple markup language used to create hypertext documents that can be viewed on a variety of computing platforms. A markup language is designed to represent the data structures of a given document (e.g., title, headings) for storage, processing, and transmission. One of the increasing numbers of Document Type Definitions (DTDs) of the International Standards Organization's Standard

Generalized Markup Language[14] (SGML), HTML conforms to SGML through the use of structural elements such as headings, lists, buttons, and embedded images. In an HTML document, these elements are combined to present the document in a form that can be read by any WWW client application.

HTML has been the principal language of the WWW since 1990 and is primarily responsible for the appearance of WWW data to the user. HTML has gone through two revisions since 1990. HTML 2.0 was an upgrade of the formal standard that added new features such as figures, tables, and forms in 1994. HTML 3.0 is expected to become an Internet standard in 1996 and will support the use of style sheets and handle text flow around figures, math equations, custom lists, and tables. As expressed by Dan Connolly of the W3C, "HTML 3.0 offers expressive capabilities similar to those provided in word processing programs."[28]

HTML markup can represent hypertext news, mail, documentation and hypermedia; menus of options; database query results; simple structured documents with in-lined graphics; and hypertext views of existing bodies of information. As mentioned earlier, HTML is a MIME Content Type (RFC 1521) and has been designed to be a simple format for providing linked information.[30]

Augmenting the WWW

The early and enthusiastic acceptance of WWW technology is due to a number of factors. Perhaps the most important is that the WWW provides an inexpensive, widely available, and easy-to-implement universal client–server pardigm that supports the widespread distribution of hypertext documents. In the past, building Internet-based information systems was a complex process in which developers had to create client applications for multiple platforms. The WWW provides an elegant solution to this problem in that Web clients capable of interpreting standard HTML documents are available on a wide range of platforms. In order to create a cross-platform, Internet-based information system, the developer need only set up a WWW server on his or her platform of choice and using standard HTML be assured that users on all major platforms will be able to access the server.

The success of the WWW has spawned a series of software-based enhancements to HTML and HTTP. While HTML offers a rich set of cross-platform text formatting features, many WWW publishers are beginning to use the Portable Document Format (PDF)[45] developed by Adobe Software. This platform-independent file format (based on Postscript Level 2) allows one to compose complex page layouts of text and graphics and then capture them in a PDF file, which is then referenced in an HTML document. PDF readers, such as Adobe Acrobat Reader, are freely available for most major computer platforms and provide PDF display capability to WWW clients. PDF applications such as Adobes's Acrobat allow one to compose complex documents, using a variety of styles and formats, in a sophisticated graphic WYSIWYG (What You See Is What You Get) editing environment and then save that document as a WWW-publishable PDF file. PDF documents support embedded hypertext and WWW URL links. The Centers for Disease Control and Prevention (CDC) now makes its *Morbidity and Mortality Weekly Report* (*MMWR*) and other documents freely available in PDF format on its WWW server.[51]

The cross-platform capability of the WWW applies not only to text but also to still images, digital video, and sound. This platform-independent multimedia delivery is achieved by the use of standard multimedia data formats (such as GIF and JPEG[16] for still images, Quicktime and MPEG[15] for digital video, and AIFF for sound) referenced within HTML documents. These multimedia data types are presented "in-line" by the WWW client software or are forwarded to external "helper applications" on the user's machine. For example, a WWW client such as the National Center for Supercomputing Applications' (NCSA's) Mosaic[79] will download an MPEG digital video file from a WWW server to the user's computer and then automatically invoke an external "helper" application to display the MPEG-encoded video in an external window. The use of "helper applications" is likely to decrease as WWW clients begin to handle standard multimedia formats internally. This may be achieved by the integration of proprietary "media viewers" into the WWW client software. This integration may also have the effect of standardizing the multimedia formats used on the WWW to a small set of core formats. The display of composed multimedia documents or complete multimedia presentations on the WWW will also be supported by the inclusion of proprietary "player engines" within WWW clients. For example, in June 1995 the Netscape Corporation (Mountain View, CA) and Macromedia Inc. (San Francisco, CA) agreed to integrate Macromedia's Director multimedia playback software into the Netscape Navigator WWW browser, thus allowing WWW access to sophisticated multimedia documents created with Macromedia's Director software.

An interesting extension to the idea of downloading multimedia data from WWW server to client is the

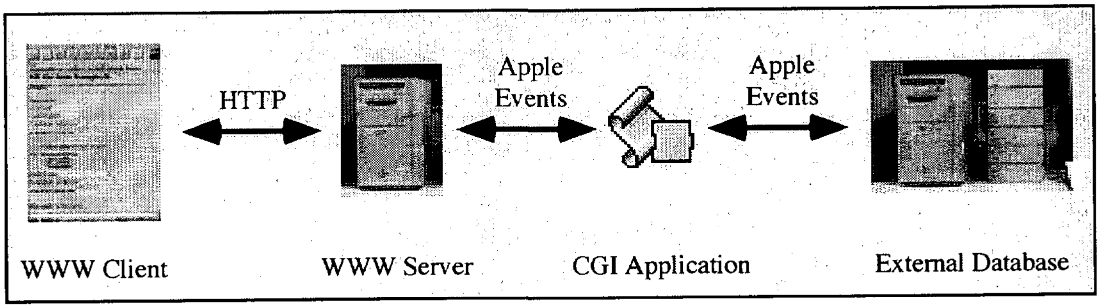

Figure 1 Relationship of the World Wide Web (WWW) server to Macintosh National Center for Supercomputing Applications (NCSA) Common Gateway Interface (CGI) application. HTML = Hypertext Markup Language.

dynamic transfer of computer "bytecode" (computer code running on a virtual machine) to augment the functionality of WWW clients. This approach is being pioneered by Sun Microsystems "Java"[60] software, which uses embedded systems technology to include software modules (called "Applets") in HTML pages. An applet is a program, written in the Java language, that can be referenced in an HTML page, much like an image can be included. When one views a page that contains an applet, the applet's code is transferred to the client computer and executed. This technology has considerable potential for enhancing the functionality of WWW client applications to support features such as real-time animation image processing, interactive simulation, and data analysis. The Netscape Corporation recently licensed Sun's Java technology and will include it in Netscape WWW browsers by the end of 1995.

A more widely used method of augmenting the WWW client–server model is the use of applications supporting the NCSA Common Gateway Interface (CGI) standard.[43] CGI allows external programs to interface with information servers such as WWW servers. For example, a CGI application can be used to support a WWW interface to an external database by translating queries received from a WWW client into queries appropriate for the database. The CGI would then send this query to the database and convert the retrieved data to HTML for transmission to the WWW client. How CGI applications communicate with external applications is platform-specific. For example, on the Apple Macintosh platform, many CGIs use AppleEvents to effect this communication (Fig. 1).

CGIs can be written in a wide range of languages such as Applescript, C, C++, and PERL. Some common WWW tasks implemented by CGIs include password-restricted access to WEB pages, HTML forms processing, sending electronic mail from within WWW clients, and displaying statistics on WWW server access. The CGI standard has contributed to the success of the WWW by providing developers with the capability to expand the functionality of HTTP and by providing a mechanism for piping data between the WWW server and external applications.

NCSA has also developed an experimental Common Client Interface (CCI) that allows external applications to communicate with the NCSA Mosaic client via TCP/IP. Applications can use Mosaic to fetch URLs or ask Mosaic to report the URLs selected by the user. Applications written to support CCI can transfer data from the WWW to the local program space, essentially turning the client program into a potential WWW browser itself. Currently (November 1995), only NCSA Mosaic for X supports CCI.

An alternative approach to augmenting WWW clients uses component-based software architectures such as OpenDoc.[48] Apple Computer recently announced its intention to release CyberDog,[66] an Internet-based application that will use the OpenDoc standard to provide a general-purpose Internet access tool for which third-party developers can provide external "parts" to handle tasks such as image manipulation, database access, and electronic mail.

Currently, WWW clients are limited to the display of two-dimensional text and graphics, but the emergence of VRML[53] (Virtual Reality Modeling Language) will provide a method for interactive exploration of three-dimensional (3D) data over the Internet. VRML is an open, platform-independent, file format for 3D graphics on the Internet. Similar in concept to the Web standard HTML, VRML encodes computer-generated graphics into a compact format for transmission over a network. As with HTML, a user can view the contents of a file (in this case an interactive 3D graphics file) as well as navigate to other VRML "worlds" or HTML pages. OpenInventor, a widely accepted, object-oriented 3D graphics toolkit developed by Silicon Graphics (Mountain View, CA), provides the framework for VRML. This exciting technology will make it possible for users to interact with data in a virtual, 3D cyberspace. VRML may also allow users to manipulate 3D data sets such as magnetic resonance imaging and computed tomography reconstructions via the WWW.

WWW servers can be created using inexpensive microcomputers and freely available server software. While direct Internet connections are desirable, acceptable performance can often be obtained using high-speed modems and conventional telephone lines to connect to a server using the Serial Line Interface Protocol[36] (SLIP), the Point-to-Point Protocol[39] (PPP), or similar communications methods. In addition, Integrated Services Digital Network (ISDN), where it is available, also offers an alternative to direct Internet connections.

SLIP allows desktop PCs to perform internetworking essentially as UNIX terminals using "serial ethernet" for data communications. SLIP is a "packet-framing protocol" that allows computers to easily exchange Internet Protocol (IP) packets, the basic data unit of the Internet. With a standard voice grade telephone line, a modem, and SLIP software, any SLIP-enabled desktop PC can connect to the Internet.

PPP was developed by the IETF and designed to provide temporary links between local area networks (LANs) over telephone lines. PPP differs from SLIP in that it provides a method for the establishment, configuration, and evaluation of serial linkages as well as encapsulating the data that travel over these links. In addition, PPP supports the establishment and configuration of different network-layer protocols, e.g., IP, IPX (Novell, Orem, UT). PPP is rapidly replacing SLIP and is becoming the de facto standard for serial-based Internet connections.[26]

With a SLIP/PPP connection, one can open multiple network connections or sessions on his or her desktop PC and perform multiple tasks. For example, one can open an FTP window, download a file, read news, Telnet to a remote host, and connect the WWW using freely available WWW browsing software.

ISDN offers the user relatively inexpensive "dialed digital access" to the telecommunications network and the Internet; eliminating the need for leasing expensive dedicated high-speed telephone lines. In tandem with data transmission protocols such as PPP, well suited for ISDN because of its initial design as a method of communicating via point-to-point links over telephone networks,[38] ISDN and its services are gaining increasing popularity with Internet users looking for direct Internet connectivity at a reasonable cost. The popularity of the Internet and the phenomenal growth of the WWW are bringing increased interest in ISDN and a corresponding growth in its availability nationwide.[32]

Extensions to WWW technology are intended to address both the needs of users and the perceived shortcomings in the underlying technology. However, as a commercial competition between vendors increases, it is important to note that there is a potential conflict between proprietary extensions and the open standards process that has made the WWW a success.

Data Security and the WWW

WWW development is being increasingly driven by the commercial sector. As more and more companies do business on the Internet, the problems of implementing secure financial transactions and ensuring data protection assume an increasing importance. Health care applications on the WWW that involve confidential patient information must also contend with similar security issues and will probably inherit many of the solutions currently being defined for use in the business sector. A detailed discussion of Internet security is beyond the scope of this paper, and we will limit our discussion to issues specific to the WWW.

There are two major approaches to securing WWW information systems. The first strategy involves protecting individual servers and network sites. For example, many commercial WWW servers allow the administrator to restrict connections from clients at specific IP addresses or domains. If one is setting up a WWW-based information system for use within a specific institution or by users at predefined sites, this feature can be very helpful in excluding potential intruders. However, for WWW services open to all comers, this strategy is of limited utility. In general, administrators usually rely on network perimeter security schemes such as firewalls[31] (gateways controlling data communications between local networks and the Internet) and user authentication.

Even if the WWW server is secure, the data transmitted between server and clients using HTTP is not encrypted or protected in any way. Using freely available network software, unscrupulous individuals could acquire and alter or eavesdrop on data transmissions containing sensitive medical or financial information. The second major approach to ensuring WWW security therefore focuses on securing client–server transactions to prevent "data snooping," ensure data integrity, and authenticate users.

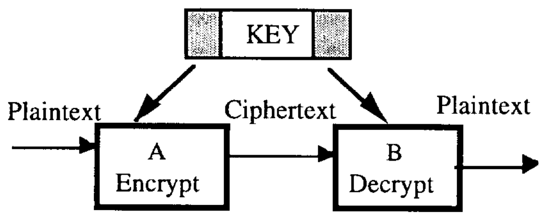

Figure 2 A symmetric cryptosystem.

These issues can be addressed by creating a secure data channel over which client–server communication occurs and by securing the actual data that are transmitted.

The Secure Sockets Layer (SSL)[42] system developed by the Netscape Corporation is the leading secure-channel technology. The principal WWW document security scheme is the Secure Hypertext Transport Protocol (SHTTP)[49] developed by CommerceNet, a nonprofit consortium that includes leading computer and banking companies. Both SSL and SHTTP have been submitted to the IETF as Internet Drafts. In early 1995, Terisa Systems (Menlo Park, CA) announced SecureWeb[61]—a WWW security system that combines both SSL and SHTTP into a platform-independent WWW security toolkit. SHTTP provides security services for transaction confidentiality, authenticity/integrity, and non-repudiability of origin.[50]

Both SSL and SHTTP rely heavily on encryption technology. The process of encryption involves the transformation of a normal data item (*plaintext*) into an incomprehensible data item (*ciphertext*). Decryption reverses this process to enable an authenticated (authorized) user to view the original data item or plaintext. There are presently two families of cryptosystems in widespread use: *symmetric* (or private-key) systems and *public-key* (asymmetric) systems. A full discussion of the mathematics behind encryption in general or specific cryptosystems is beyond the scope of this paper.

Symmetric cyrptosystems are distinguished by the fact that the same key is used for both encryption and decryption (Fig. 2). If two individuals or systems wish to communicate securely (in this case, A and B), they can use the same key to encrypt/decrypt each other's messages. A problem with this scheme is that if a third party acquires this key, then security is compromised.

Asymmetric cryptosystems employ two different and separate keys, a public key and a private key, for encryption and decryption (Fig. 3). This scheme is more secure than the single key symmetric system and is widely used to encrypt transmitted data and authenticate communications sessions over the Internet.

The private key is a secret key similar to that used in symmetric cryptosystems. The public key is freely available to all. The RSA (RSA Data Security Inc.) and ElGamal algorithms are the two most widely used encryption schemes used to implement public key–private key cryptosystems.[25] RSA technology is used by both SSL and SHTTP systems to encrypt WWW documents and authenticate clients.

As SSL and SHTTP technologies are being integrated into a commercially available toolkit for WWW developers, some of the original architects of the WWW, such as Tim Berners-Lee, are working to create Shen,[65] an alternative security scheme for the WWW. When implemented, Shen will provide mechanisms for both authentication and data encryption.

Security will be a major issue in determining the feasibility of WWW-based clinical information systems. The emerging standard for secure channels and document encryption on the WWW should help provide adequate protection for sensitive clinical information. When combined with the standard strategies for ensuring the integrity of clinical information systems, these technologies will make the WWW a secure platform for developing innovative biomedical applications.

Biomedical Applications of the WWW

Currently, one finds a diverse selection of medical WWW servers. The most common type of server represents the activities of a particular institution or group. For example, the Section of Medical Informatics at the University of Pittsburgh maintains a WWW server[59] that contains information on its research activities and fellowship program. Federal agencies such as the National Institutes of Health (NIH), the National Cancer Institute[52] (NCI), and the National Library of Medicine[54] (NLM) were early adopters of this technology to distribute information related to patient care, research, and education. NCI's CancerNet provides free access to the Physicians Data Query (PDQ) database[13] and fact sheets on various cancer topics. NLM's HyperDoc WWW server[59] contains pointers to important resources related to AIDS, cancer, medical informatics, molecular biology, and NLM's Visible Human project.[55] In addition, NLM's Health Services/Technology Assessment Text (HSTAT) WWW server contains the Agency for Health Care Policy and Research (AHCPR) Clinical Guidelines and NIH's Consensus Development Conference statements.

A number of WWW servers provide access to important health sciences information resources previously available only in paper format. The CDC[46] now offers a server containing its *MMWR*, including back issues and supplements. WWW-based, peer-reviewed, medical journals are beginning to emerge. Examples include *The Journal of Medical Imaging*[70] and *The Journal of Computational Biology*.[69]

A number of groups have developed WWW servers to support clinical decision support and education. One notable example is The Virtual Hospital (VH) initiative based at the University of Iowa. The VH site is a continuously updated medical multimedia database available 24 hours a day. The goal of this project is to provide patient care support and distance learning opportunities to practicing clinicians. "VH information may be used to answer patient care questions, thus putting the latest medical information at physicians' fingertips. This same information may be used for Continuing Medical Education (CME); delivering CME to physicians' offices and homes at a convenient time and location."[73] The project uses WWW sotware to store, organize, and distribute multimedia textbooks that incorporate features such as free-text searching, audio, video, and still images.

Many of the first biomedical WWW servers were essentially electronic document systems offering only basic navigational interactivity. However, HTTP/HTML now supports interactive documents containing features such as sensitive image maps and standard graphic user interface items such as buttons, scrolling lists, tables, and pop-up menus. These features support an interactive, graphic, client–server paradigm in which a user can navigate through large biomedical multimedia databases using a familiar "point-and-click" metaphor.

A more powerful feature of the current HTTP/HTML standard is the support of data entry "forms" that allow the WWW server to accept user-entered data using standard GUI elements such as edit fields and pop-up menus. Using CGI applications, these data can then be recorded, by the WWW server, for later analysis, or more importantly, the data can be used to drive applications external to the WWW server such as databases or electronic mail programs.

A number of biomedical form-based applications are currently under development. NLM has developed a WWW-based system for assisted searching of MEDLINE and other MEDLARS databases. This software, called Internet Grateful Med, is an evolution of the Coach[17] system developed by NLM for use with Grateful Med.[12] The Internet Grateful Med Web server, augmented by extensive additional code written at

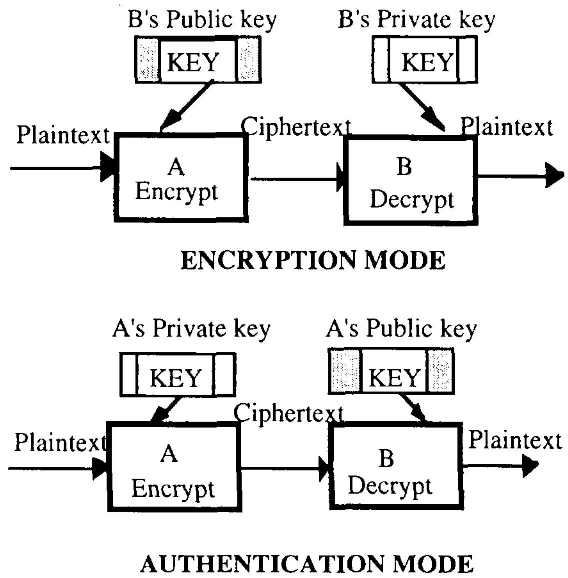

Figure 3 A public-key cryptosystem.

NLM, uses the UMLS Metathesaurus to help a searcher construct, execute, and refine MEDLINE queries. The software includes an integrated Metathesaurus browser that maps user terms through the UMLS Metathesaurus to MeSH headings. The current Internet Grateful Med prototype also supports direct links to the full text of the Clinical Practice Guidelines supported by the AHCPR—available from NLM on the Health Services/Technology Assessment Text (HSTAT) World-Wide Web server. Internet Grateful Med illustrates how one can build powerful, easy-to-use, cross-platform WWW interfaces to complex database systems. NLM is also developing a WWW interface to its UMLS Knowledge Source Server[78] that provides an easy-to-use interface for browsing the UMLS Metathesaurus.

Using the "forms" capability of WWW servers, one can take advantage of the WWW's universal client–server paradigm to offer widespread access to important biomedical databases without having to develop an Internet-based client–server system de novo. For example, NLM's On-line Images from the History of Medicine[56] is a WWW-based system providing access to nearly 60,000 images (reproducing photographs, artwork, and printed texts) drawn from the extensive (and much larger) collection of the History of Medicine Division at NLM.

As this CGI-based forms capability develops, one may anticipate that the WWW will become an important mode of access to clinical information systems. Currently, a number of WWW-based systems are under development. At Columbia-Presbyterian

Medical Center in New York, the Medical Informatics group are prototyping a WWW-based interface to their clinical data and vocabulary servers.[33] The ARTEMIS project[47] at the University of West Virginia will make clinical information available electronically to remote providers via a WWW server and their Web* software. A research group based at the Boston Children's Hospital and MIT is working on a project,[44,72] funded by NLM and AHCPR, to develop a WWW-based, multimedia interface to the electronic medical record that supports customization for specific clinical environments and needs. At the University of Pittsburgh, the Image Engine project,[74,75] funded by NLM's High Performance Computing and Communications (HPCC) program, is exploring ways of providing access to clinical images and associated reports via a WWW interface to an object-oriented, client–server database system. Other clinical WWW servers are under development at Massachusetts General Hospital[29] and Stanford.[71]

The growing acceptance of the WWW and its underlying protocols by the medical community suggest an increasing use of this technology in the clinical environment. In addition to the security concerns discussed previously, there are a number of potential problems that must be solved by developers when creating WWW information systems. As mentioned earlier, HTTP is a stateless client–server protocol in which a client connects to a server, makes a request, and then disconnects. While this reduces the load on the server side, it makes it difficult for the server to maintain state information for a client–server session, which may consist of many connections/requests. Many WWW developers have created proprietary solutions to this problem. A number of commercial WWW servers (such as that sold by the Netscape Corporation) now support extensions, called "Cookies,"[41] to handle this issue. Using this technology, a server, when returning an HTTP object to a client, may also send a piece of state information, which the client will store. Included in that state object is a description of the range of URLs for which that state is valid. Any future HTTP requests made by the client that fall in that range will include a transmittal of the current value of the state object from the client back to the server. This simple mechanism provides a powerful tool that enables a host of new types of applications to be written for Web-based environments.

While the hypertext paradigm built into the WWW is one of its greatest assets, it also makes development of WWW-based clinical information systems more difficult because of the limited navigational aids and restraints built into most WWW browsers. After traversing several hypertext links, the user may become confused as to where he or she is in the document hierarchy. In addition, because WWW client applications usually maintain a list of previously accessed pages, which the user can return to using standard WWW navigational controls, it may be difficult to ensure that the user views only the most up-to-date version of a document. For example, if the user views WWW page X containing a patient problem list and then modifies that list, resulting in a new WWW page Y, both page X and page Y remain in the navigational hierarchy. There are both human interface and server logic solutions to this type of problem, but they need to be addressed by each WWW development project rather than by built-in server features.

Lifelong Learning and the WWW

CME via the WWW is a development that offers much promise. *Martindale's Health Science Guide*,[77] an important and innovative "Health science multimedia education and specialized information resource center," is now available on the WWW. Coauthored by Jim Martindale,[76] Frank Potter,[80] and the School of Physical Sciences at the University of California at Irvine,[81] the guide features a variety of "virtual centers" of medicine, dentistry, veterinary medicine, pharmacy, nursing, public health, nutrition, and allied health. An evolving entity, the guide contains more than 3,100 multimedia health science teaching materials, 3,900 multimedia medical cases, one multimedia CME course (Category 1), 47 multimedia medical school courses/textbooks, 33 multimedia health sciences-related graduate/undergraduate courses, and a growing number of multimedia images and movies that are health sciences-related.

The Department of Pathology of the Uniformed Services University of the Health Sciences in Bethesda, Maryland, now offers Category 1 CME credits to physicians who work with its WWW-based surgical pathology cases.[58]

The Loyola University Medical Education Network (LUMEN)[27] is a WWW-based medical education project at Loyola University in Chicago, Illinois. LUMEN aims to provide access to medical education resources using hypertext and the WWW. Basic goals of the project include: 1) the integration of basic and clinical science curricular content; 2) access to medical information worldwide; and 3) the development of education hypermedia.

The goal of University of Chicago's Phoenix Project[24] is to develop an integrated academic information system that will provide full Internet connectivity and distributed hypermedia-authoring capability to the biologic sciences community at the university. One program developed through this project is Case Studies in Environmental Medicine, a self-instructional unit on hazardous substances in the environment.

The CliniWeb Project[57] at Oregon Health Sciences University is developing a WWW-based system for providing quick and easy access to biomedical information on the WWW using NLM's MeSH vocabulary (currently only the Disease Hierarchy is used) to classify information. This approach may improve information retrieval by allowing the user to search for WWW-based information using a controlled, biomedical vocabulary.

The WWW and Decision Support

Until recently, most clincians and other health professionals used computers primarily as a research tool in the retrieval of bibliographic citations to articles published in the medical literature.[22] The WWW, by providing easy access to a wide variety of medical information resources, may dramatically change the way health providers use computer and networking technology in patient care. Projects such as the VH, *Martindale's Health Science Guide*, and the LUMEN project suggest the advent of the "ubiquitous organization."[21] In this case, the ubiquitous organization would be a digital representation of much of the information and services available in a physical organization. Essentially, the ubiquitous organization amplifies and extends the power and reach of the physical organization through time and space. These projects represent an emerging electronic extension of the medical center with broad applications in areas such as telemedicine, rural health care delivery, and community medicine.

In the medical decision-making process, the clinician must often assess information available in local and remote databases. In a health care environment that may be increasingly dominated by a reliance on primary care, especially in rural and other medically underserved areas, the WWW offers much promise in both the dissemination and the retrieval of medical information. "These solo practices are potentially a direct source of information concerning the profile of health and disease in the community as well as the variety of treatment and prevention activities being undertaken and the effectiveness of these activities."[23]

One example of WWW-based clinical decision support is the University of Pennsylvania's OncoLink[20] WWW project. OncoLink was initially designed to service the information needs of clinicians in pediatric oncology, radiation oncology, medical oncology, surgical oncology, medical physics, and human services, as well as their patients. Over time, patients and other users began to suggest a more disease-oriented approach. As a result, OncoLink now functions as a major WWW resource for oncology and patient-oriented cancer information.

The WWW can potentially support consistent and effective health promotion and diesease prevention strategies to both the health care provider and the patient. The existence of easily accessible clinical and patient information resources on the WWW will likely change the traditional clinician–patient relationship as both parties use these resources to educate and inform themselves and each other about diagnosis, therapy, and prognosis.

Conclusion

The WWW is an important, evolving informatics technology that may have a significant impact on biomedicine by dramatically improving the ease with which we distribute and access information via the Internet. The success to date of the WWW may be attributed in large part to its ease of use, its platform-independent client–server software, the wide availability of inexpensive WWW browser applications, and its support of distributed hypertext and multimedia. Use of the WWW for financial transactions has resulted in the development of a number of technologies designed to make Internet-based communication secure. These encryption-based technologies will facilitate the creation of secure wide-area access to clinical information systems via the Internet. The WWW represents a first, promising, step toward a global information network that may radically alter the way we retrieve and use information in the practice of medicine.

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35. http://ds.internic.net/ietf/ietf-description.txt
36. http://ds.internic.net/rfc/rfc1055.txt
37. http://ds.internic.net/rfc/rfc1341.txt
38. http://ds.internic.net/rfc/rfc1618.txt
39. http://ds.internic.net/rfc/rfc1661.txt
40. http://ds.internic.net/rfc/rfc1738.txt
41. http://home.mcom.com/newsref/std/cookie_spec.html
42. http://home.mcom.com/newsref/std/SSL.html
43. http://hoohoo.ncsa.uiuc.edu/cgi/overview.html
44. http://luke.lcs.mit.edu/medweb/
45. http://www.adobe.com/Acrobat/Acrobat0.html
46. http://www.cdc.gov/
47. http://www.cerc.wvu.edu/nlm/nlm.html
48. http://www.cilabs.org/

49. http://www.commerce.net/cgi-bin/textit?/information/standards/drafts/shttp.txt
50. http://www.commerce.net/information/standards/drafts/shttp.t
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60. http://www.sun.com:80/sunworldonline/swol-07-1995/swol-07-java.html
61. http://www.terisa.com/prod/prod.html
62. http://www.w3.org/hypertext/WWW/Addressing/Addressing.html
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Appendix

A Review of Medical Applications and the World Wide Web—An Emerging Health Care Information Management Model: Selected WWW Servers Active as of 9/1/95

I. WWW Servers to Begin Internet Exploration

1. CMC Information Resources
   http://www.rpi.edu/Internet/Guides/decemj/icmc/toc3.html
2. WWW Search Engines
   http://web66.coled.umn.edu/WWWinfo/meta-index.html
3. WWW FAQ
   http://sunsite.unc.edu/boutell/faq/www_faq.html
4. WWW Project History
   http://monge.univ-mlv.fr/History.html
5. The Whole Internet Catalog
   http://gnn.com/wic/index.html

II. URLs for WWW Development

1. WWW Development
   http://www.charm.net/~web/Vlib.html
2. A Beginner's Guide to URLs
   http://www.ncsa.uiuc.edu/demoweb/url-primer.html
3. WWW Names and Addresses, URIs, URLs, URNs
   http://www.w3.org/hypertext/WWW/Addressing/Addressing.html
4. A Beginner's Guide to HTML
   http://www.ncsa.uiuc.edu/demoweb/html-primer.html
5. HTML Editors
   http://akebono.stanford.edu/yahoo/Computers/World_Wide_Web/HTML_Editors

III. URLs for Locating WWW Client Software

1. Netscape—A multiplatform WWW Browser
   http://home.mcom.com/home/welcome.html
   ftp://ftp.mcom.com/netscape/
2. Mosaic—The Best-known WWW Browser
   http://www.ncsa.uiuc.edu/SDG/Software/Mosaic/Docs/help-about.html
   - MAC: ftp://ftp.ncsa.uiuc.edu/MAc/Mosaic/
   - PC Windows: ftp://ftp.ncsa.uiuc.edu/Mosaic/Windows
   - X Windows: ftp://ftp.ncsa.uiuc.edu/Mosaic/Unix/
3. MacWeb—A full-featured Macintosh WWW Browser
   http://galaxy.einet.net/EINet/MacWeb/MacWebHome.html
   ftp://ftp.einet.net/einet/mac/macweb
4. Lynx—An ASCII Terminal WWW Browser

tp://ftp2.cc.ukans.edu/pub/lynx/

5. Emacs—An Emacs Subsystem Providing a Means to Browse the WWW That Runs under UNIX
   http://www.sinica.edu.tw/simtel/simtel_index_freemacs.html
   ftp://ftp.uu.net/systems/gnu/xemacs/

IV. URLs for Locating WWW Server Software

1. CERN—The Original WWW Server
   http://www.w3.org/hypertext/WWW/Daemon/Status.html
2. MacHttp—A WWW Server for the Macintosh
   http://mijuno.larc.nasa.gov/MHI/MacHTTPinfo.html
3. Http for Windows/NT—A WWW Server for Windows/NT
   http://info.cern.ch/hypertext/WWW/HTTPS/Status.html
4. NCSA—A WWW Server for Files That Runs under UNIX
   http://info.cern.ch/hypertext/WWW/NCSA_httpd/Overview.html
5. SerWeb—A WWW Server That Runs under Windows 3.1
   http://riskweb.bus.utexas.edu/www.htm
6. Netscape—A Multiplatform WWW Browser
   http://home.mcom.com/
   ftp://ftp.mcom.com/netscape/

V. Medical WWW Servers

1. Martindale's Health Science Guide—'95
   http://www-sci.lib.uci.edu/~martindale/HSGuide.html
2. The Department of Pathology of the Uniformed Services of the Health Sciences
   http://wwwpath.usuf2.usuhs.mil/default.html
3. The Virtual Hospital
   http://vh.radiology.uiowa.edu/
4. *Morbidity & Mortality Weekly Report*
   http://www.crawford.com/cdc/mmwr/mmwr.html
5. Hospital Web
   http://dem0nmac.mgh.harvard.edu/hospital web.html
6. PDQ NCI Gopher
   gopher://gopher.nih.gov:70/11/clin/cancernet/pdqinfo
7. The Virtual Medical Center
   http://www-sci.lib.uci.edu/~martindale/Medical.html
8. OncoLink (Penn)
   http://cancer.med.upenn.edu:80/
9. LUMEN Home Page: Loyola University Medical Education Center
   http://scuba.meddean.luc.edu:80/lumen/
10. Image Engine WWW Server
    http://dublin.smi.med.pitt.edu/ImageEngine/ImageEngine.html
11. Medical Illustrators' Home Page
    http://siesta.packet.net/med_illustrator/Welcome.html
12. ANCPR Clinical Guidelines
    http://text.nlm.nih.gov/ahcpr/ahcprc.html
13. CancerNet
    http://biomed.nus.sg/Cancer/welcome.html
14. Clinical Preventive Services Guidelines
    http://text.nlm.nih.gov/cps/www/cps.html
15. HIV/AIDS Database
    http://text.nlm.nih.gov/atis/list.html
16. Medical Sciences Bulletin
    http://pharminfo.com/pubs/msb/msbmnu.html#msb_contents
17. Virtual Library: Biosciences–Medicine
    http://golgi.harvard.edu/biopages/medicine.html
18. MSDS Healthcare Standards Home Page
    http://dumccss.mc.duke.edu:/ftp/standards.html
19. National Cancer Institute Home Page
    http://www.NCI.NIH.gov//
20. Yahoo: Health: Medicine
    http://akebono.stanford.edu/yahoo/Health/Medicine/
21. Pharmaceutical Information Network Home Page
    http://pharminfo.com/pin_hp.html
22. U.S. Department of Health and Human Services
    http://www.os.dhhs.gov/

VI. Medical Informatics Selected WWW Servers

1. American Medical Informatics Association
   http://amia2.amia.org/
2. CAMIS (Stanford)
   http://camis.stanford.edu/
3. Columbia Medical Informatics
   http://www.cpmc.columbia.edu/"ADD_DATE
4. Decision Systems Group (Harvard)
   http://dsg.harvard.edu/
5. Duke Medical Informatics
   http://dmi-www.mc.duke.edu/default.htm
6. MGH Laboratory of Computer Science (Harvard)
   http://lcs-guide.mgh.harvard.edu/
7. National Library of Medicine
   http://www.nlm.nih.gov/
8. OHSU Medical Informatics
   http://www.ohsu.edu/
9. University of Pittsburgh Section of Medical Informatics
   http://kappa.smi.med.pitt.edu/welcome.html
10. University of Utah Department of Medical Informatics
    http://www.medlib.med.utah.edu/medinfo/main.html
11. Vanderbilt Division of Biomedical Informatics
    http://vumclib.mc.vanderbilt.edu/dbmi/
12. Yale Center for Medical Informatics
    http://paella.med.yale.edu/