# JPEG at 25: Still Going Strong

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Photographic images are taken for granted today as part of the multimedia mix of information we use daily to communicate in both our personal and professional lives. An enabling technology for this is the photographic coding technique, universally known as JPEG, which is celebrating its 25th anniversary of receiving approval as standard this year. Where did JPEG come from, and what are the fundamental components that have given it longevity?

## The Origins

The image compression technique used for applications as diverse as photography, webpages, medical imaging, and public records is JPEG, named after the original International Standards Organization (ISO)/International Telegraph and Telephone Consultative Committee (CCITT) Joint Photographic Experts Group, established in November of 1986. The group developed the technique in the late 1980s and produced the international standard, formally known as Int'l Telecommunication Union (ITU)-T T.81, in the early 1990s.[1]

## How It All Began

In the early 1980s, some of the leading telecommunication service providers around the world were launching videotex services: information services delivered over analog telephone lines to a terminal based on a television set or to an inexpensive dedicated terminal (see Figure 1). Such services were also delivered to PCs once they became available. The technology was primitive by today's standards. The data rates available using a modem over a copper telephone pair were generally 1,200 (download)/75 (upload) bits/s, although up to 4,800 bits/s was possible.

Later in the decade, the 64 kbits/s integrated services digital network (ISDN) was introduced, and many assumed it would eventually become widely available. At that time, Cathode Ray Tube displays were capable of resolutions up to 640 × 400 pixels, and advanced televisions had text and graphics display controllers for teletext. Some even had microprocessors, but RAM was expensive and was typically limited to a few kilobytes. Following the Commodore Pet and Apple 2 computers, the IBM PC was launched. These early machines had displays supporting graphics and color, but they didn't have photographic display capability.

With the advent of ISDN, telecommunication companies' research centers looked for ways to improve their videotex service offerings by enhancing display capabilities, using computer (geometric) graphic and photographic image coding techniques. However, photographic images contain a lot of information. The ITU-R Digital Studio Television Picture Standard recommendation[2] was taken as reference for this early work on picture coding. A full-frame 601 picture has 720 × 575 pixels, as illustrated in Figure 2. It uses a color encoding system known as YCbCr 4:2:2. The chrominance components, Cr and Cb, have half the resolution of the luminance component Y. All components are represented by 8 bits, giving an average of 16 bits per pixel, requiring 828 kbytes per frame for storage and transmission. Even at the ISDN rate of 64 kbits/s, it would take more than 104 s to transmit a full frame.

A great impetus to the international development and evaluation of picture coding techniques was the formation of the European Strategic Program for Research in Information Technology (ESPRIT) project 563—Photovideotex Image Compression Algorithms (PICA) in 1985 (Table 1 lists this and other historical milestones).[3,4] The consortium of seven partners had experience in telecommunications, broadcasting, and computing (see Table 2). The core team included picture coding experts from leading European telecommunication laboratories already involved in international standards activity (see Figure 3). Throughout the PICA

project's lifetime (1985–1988), key contributions were made to the JPEG technical kernel and to application requirements and the evaluation of coding techniques. In particular, the project developed and evaluated 10 techniques, and two were submitted for standardization (and one of those two was the central part of the future JPEG standard).

## Evolving International Standards

Videotex standards were being worked on by international standards bodies responsible for text, graphic, and image coding at CCITT, CEPT (Conférence Européenne des Administrations des Postes et Télécommunications), and ISO. Digital image coding work had typically focused on facsimile, slow-scan television, and teleconferencing. The early work on photographic coding initiated by three European telecommunication labs—British Telecom Labs, CSELT (Centro Studi e Laboratori Telecomunicazioni), and CCETT (Centre Commun d'études de Télévision et Télécommunications)—was presented to the international standards bodies, first in 1982 at CEPT, and later to ISO and CCITT.

In 1982, ISO TC97/SC2 established Working Group 8, chaired by Zak Muscati (Department of Communications of Canada) and later by Hiroshi Yasuda (Nippon Telegraph and Telephone, Japan). The working group was established to define the principles of graphic and photographic coding. Early in 1986, during a meeting in Boston, the scope and progress of the ESPRIT project was presented to this group.

In CCITT Study Group VIII (SGVIII), a special rapporteur's group was formed in 1985 to investigate new forms of image communication. The group was initially chaired by Manfred Worlitzer (Deutsche Bundespost, Germany). Then, in 1987, István Sebestyén (Siemens, Germany) took over. The group analyzed the different coding types (text, graphic, geometric, incremental, and photographic) required for different telecommunication services (facsimile, teletext, videotex, and teleconferencing), and they formulated requirements for common components for image communications.

Realizing the importance of picture coding for future multimedia communication services, in July 1986, the leaders of the CCITT and ISO groups proposed that the ISO Photographic Expert Group (PEG) should become a joint working group (JPEG) to select a high-performance photographic image compression techni-



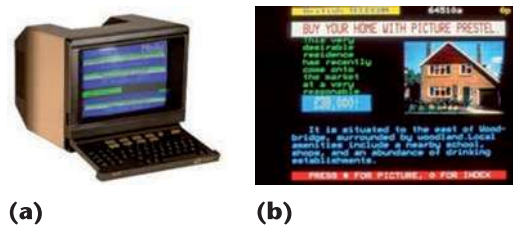**(a)**             **(b)**

*Figure 1. Information services delivered over an analog telephone line to an inexpensive dedicated terminal: (a) the Minitel terminal in France (source: CCETT; used with permission) and (b) a photovideotex page on the Prestel terminal in the UK (source British Telecom; used with permission).*
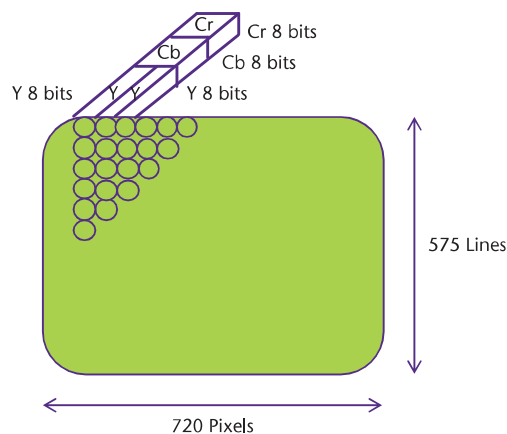


*Figure 2. The Digital Studio Television Standard. It uses 8 bits for the luminance component but half the resolution for the two 8-bit chrominance components, giving an average of 16 bits per pixel, requiring 828 kbytes per frame to store and transmit data.*

que, with CCITT setting the service requirements and ISO providing the coding expertise. The first meeting of JPEG under the chairmanship of Graham Hudson (British Telecom, UK) was in November 1986 in Parsippany, New Jersey. Following the agreement of a technique for standardization in 1988, Greg Wallace (Digital Equipment Corporation, US) took over the chair until the JPEG standard was approved first by the ITU and later by the Joint Technical Committee 1 of ISO and IEC.

## The Wish List

The JPEG working group aimed to find and standardize a compression technique that could be used for a broad range of continuous tone images for applications, ranging from

**Table 1. Historical milestones.**

| Date/location | Milestones |
|---|---|
| 1982 | Introduce image coding for videotex at CEPT (Conférence Européenne des Administrations des Postes et Télécommunications) |
| June 1985, Ipswich | Launch the European Photovideotex Image Compression Algorithms (PICA) project |
| November 1986, Parsippany | ISO and CCITT form Joint Photographic Experts Group (JPEG) |
| March 1987, Darmstadt | Register coding schemes and define requirements and selection process |
| June 1987, Copenhagen | Hold initial selection meeting—10 techniques reduced to 3 |
| October 1987, Washington | Revise specification and hold first selection process |
| December 1987, Winchester | Revise specification and hold second (final) selection process |
| January 1988, Copenhagen | Hold final selection meeting—adaptive cosine transform (ADCT) technique chosen |
| June 1989, Rennes | Refine and consolidate the ADCT technique by the JPEG international team |
| 1989 | Write the JPEG draft international standard with ITU/ISO/IEC common template |
| 1992 | Approve JPEG as Recommendation ITU-T T.81 |
| 1993 | Approve JPEG as ISO/IEC 10918-1 Standard |

**Table 2. The seven partners of the European Strategic Program for Research in Information Technology (ESPRIT) project 563—Photovideotex Image Compression Algorithms (PICA).**

| Company | Country |
|---|---|
| BT Labs | UK |
| IBA | UK |
| KTAS | Denmark |
| DNL | Netherlands |
| CSELT | Italy |
| CCETT—FT Labs | France |
| Nixdorf | Germany |

photovideotex (the web had not yet been invented) to press photos and medical images.[5] They set about defining a set of mandatory requirements. An essential feature was the ability to adjust the compression factor (the reduction in data) versus the final quality to match the needs of the application.

With restricted data-rate transmission channels, the group considered it mandatory to provide a progressive picture build-up.[6] The idea was to quickly deliver a crude (lower resolution/quality) image for instant display, which could subsequently be improved in several stages until the highest quality was achieved. This facility also provides pictures of different resolution and accuracy to be held on a database and delivered to match the capability of the output device. Sequential build-up, where a full-quality image is built up, from top to bottom and line by line, was also needed for rapid picture file transfer.

The JPEG working group also realized that some applications, such as medical imaging and document archiving, required a final image to be identical to the original. This is referred to as lossless, reversible, or exact coding.

Many of the applications (such as audiographic conferencing and remote screen sharing) presenting an image to a display required the decompression in real time. This was a challenge with the technology of the time (that is, with IBM's PC Advanced Technology (AT) machine, with a 20MHz 386 processor or dedicated digital signal processors[7]), so the three algorithms in competition after the January 1987 Copenhagen meeting were required to show demonstrations of the real-time decoding.

### Choosing the Algorithm

The JPEG working group set out to define a procedure to select a coding technique. For a technique to be considered as a candidate for standardization, the proposer had to provide a full technical description and a set of agreed test pictures encoded/decoded at different compression factors. At the first JPEG meeting (Parsippany, Nov. 1986), 14 different techniques were presented, but only 12 proposals were officially registered in Darmstadt in March 1987, at the second JPEG meeting. The candidates included examples of most compression techniques known to the scientific community at the time, such as predictive coding, block coding,

cosine transform, vector quantization, and combinations of these. The key requirements for candidates for the final selection process were as follows:

- provide and present full documentation of the technique including functionality, principles, and implementation;

- prepare and conduct subjective testing of new nonstandard test images for bit rates (0.08 bit/pixel, 0.25 bit/pixel, 0.75 bit/pixel, and 2.25 bit/pixel);

- demonstrate a prototype 64 kbits/s real-time decoder with progressive build-up; and

- submit executable code.

Three techniques stood out at the initial selection process at KTAS in Copenhagen in June 1987—the European (PICA) adaptive cosine transform (ADCT) technique, the US (IBM) differential pulse code modulation (DPCM)-based technique, and the Japanese block truncation coding scheme. These three techniques were used as the basis for further development by international teams led by Europe (Alain Léger), US (Joan Mitchell), and Japan (Yasuhiro Yamazaki) respectively, for the final selection meeting held at the Copenhagen Telecom Company (KTAS) Laboratories in January 1988.

For the final selection, the test requirements were increased. Subjective testing took place at 2.25 bits per pixel, 0.75 bpp, 0.25 bpp, and 0.08 bpp using five new test images for which the candidate algorithms were not trained (see Figure 4). A double stimulus technique was employed, whereby images were compared with the original.[8]

It was evident from the subjective testing (see Figure 5) that the ADCT technique produced higher-quality results for all of the compression stages. Excellent results were achieved at 0.75 bpp (20:1 compression) and results indistinguishable from the original were produced at 2.25 bpp. ADCT real-time decompression was demonstrated in software on an IBM PC AT with a 20MHz 386 processor. The group unanimously agreed to develop a standard based on this ADCT technique.[9,10]

## Key Technical Choices

Here we explain the key technical decisions the JPEG group made during the building process of the JPEG compression scheme and format.



*Figure 3. The JPEG core team included picture coding experts from all over the world, including leading worldwide telecommunication and IT laboratories already involved in international standards activity.*

## The Transform

The scientific literature shows the optimum transform is the Karhunen-Loeve Transform (KLT). The KLT analyzes the image and extracts the principle components, thus compacting the energy very efficiently. However, it's computationally intensive—far more than realistically achievable in the late 1980s. Furthermore, the calculated transformation kernel depends on the image content, so it must be calculated for each image.

Various other simpler transforms were examined during the development of JPEG: high and low correlation transforms, where all operations can be done using only shifts and adds, and the discrete cosine transform (DCT), which can be calculated using very fast algorithms (like the Fast Fourier Transform). DCT was by far the best of the second-best options, with an energy compaction approaching the KLT. It was therefore decided to continue with DCT as the transform of choice.

Discrete wavelet transform (DWT) appeared later (with the orthogonal version appearing in 1987), which avoids blocking artifacts, but it wasn't feasible with the hardware of the day and with the speed requirements (real-time decoding at ISDN 64 kilobits per second). JPEG2000 was standardized later (after 2000) with DWT, but it was never intended to replace ADCT in JPEG (1992).

## Block Size

From an energy compaction point of view, the optimum block size should be one where the pixels in an average block are correlated. Using too small a block size misses important pixel-to-pixel correlation. Using too large a block size

*Figure 4. Some JPEG test pictures (source: JPEG; used with permission). These are examples of images used for the first and final selection process for the coding technique. (Note that these are the reproduced images. Credits for the original versions are (from left to right, top row) IBA, SMPTE, and CCETT; (bottom row) Roy Vivian, EBU, and Roy Vivian/IBA).*

tries to take advantage of a correlation that might not exist.

Working with the typical image sizes of the late 1980s (720 × 575 pixels), 4 × 4 blocks were too small to catch important correlations, and 16 × 16 blocks often contained uncorrelated pixels and increased calculation complexity for no gain. So out came the 8 × 8 block!

Today, with 4K and 8K and higher display resolutions, larger block sizes (16 × 16 or even higher) are an obvious consideration.

### Psychovisual Quantization

Having performed the discrete cosine transform on an 8 × 8 block, 64 pixel values have been transformed into 64 amplitudes of 2D cosine functions of various frequencies. The eye, however, is not equally sensitive to all frequencies. Low-frequency variation within the 8 × 8 block is much more visible than high-frequency variation. This is where quantization comes into play: low frequencies are represented with higher accuracy than high frequencies without jeopardizing the visual content of the blocks.[11] This is generally what provides lossy compression.

During the development of JPEG, researchers considered (and experimented with) the quantization of the less visible dark areas. Blocks with low DC values (dark blocks) could be quantized more harshly than blocks with medium or high DC values. Experiments showed, however, a prominent problem with such content-dependent strategies: adjacent blocks treated with different quantization matrices are visually different and thus add heavily to the annoying blocking artifacts that are seen at high compression without really improving the compression rate. In JPEG, all blocks in a given channel are quantized with the same quantization values.

### Modeling and Encoding

Transformation and quantization together produce datasets with a statistical structure that lends itself to complementary compression. The process to ensure this is the modeling (optimal-source symbols selection) and encoding of the selected symbols. Given that the majority of the quantized amplitudes are either zero or very small, and that most of the nonzero or larger quantized amplitudes pertain to the low frequencies, KTAS (primarily Jørgen Vaaben) devised an ingenious way to encode these using value pairs. The first value in the pair tells how many zero amplitudes to skip before the next nonzero amplitude (run length), and the second value in the pair tells how many bits are necessary to represent that amplitude. The value pair is then followed by the amplitude. When there are no more nonzero amplitudes in the block, an end-of-block code is emitted.

The statistical distribution of these value pairs is heavily skewed toward small values of both runs and number of bits, so the 2D
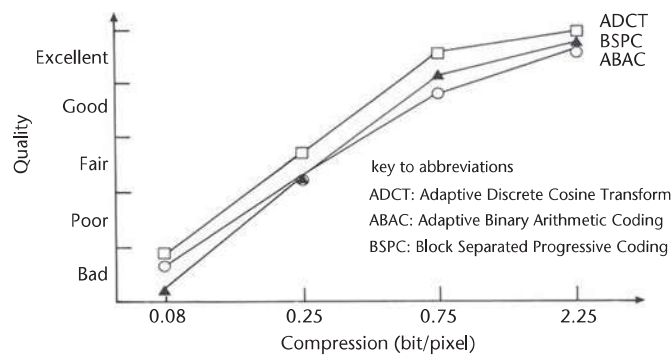
*Figure 5. Subjective testing: (a) results from the test, conducted at (b) KTAS in Copenhagen (source Joint Photographic Experts Group; used with permission).*

Huffman coding was the obvious choice. With this encoding scheme (lossless entropy coding), significantly higher compression rates were obtained in JPEG.

### Baseline and Profiles

In the early stages of drafting the standard (1988), the group proposed producing a kernel that fulfills most of the expected requirements of videotex and envisioned image telecommunication services. The results of the final selection formed the basic kernel (baseline) JPEG system. Most significantly, a royalty-free baseline system was created. On this foundation, other profiles were added like layers of an onion for specific applications and for options such as arithmetic coding. Such options might have been royalty bearing. The baseline coding scheme structure is robust and has a very low algorithmic complexity, making it easy to understand and implement. The baseline is sufficient for the many applications and is heavily used.

This patent strategy for the JPEG baseline and options proved to be most successful in supporting market penetration of the JPEG algorithm. On this basis, the Independent JPEG Group (an informal open source group under the leadership of Tom Lane) released an open source JPEG code in October 1991 (based on the draft JPEG standard). At that time, the Internet and the web badly needed a still-picture compression standard.

Later (2000–2002), it turned out that legally, the ITU, ISO, or IEC patent policy did not permit a royalty-free (RF) baseline with royalty-bearing (RB) options. Only Fair, Reasonable, and Non-Discriminatory (FRAND) terms were permitted for the whole standard. This has led to some patent litigation cases, which diminished between 2005 and 2006 when all the argued patents were running out. However, for future similar standardization projects, ideally, a Standards Developing Organization with a mixed RF and FRAND patent policy would be required.

### DC-AC Prediction

A vital part of image compression is de-correlation. DCT is close to optimal for de-correlating the values within the $8 \times 8$ pixel blocks. In the standard, the DC value of the preceding block is used as the predictor for the current block. During the development of JPEG, a scheme for a more advanced inter-block de-correlation, using AC prediction, was considered. Based on the DC values of neighboring blocks, AC values in the center block can be predicted. However, JPEG has not integrated this scheme due to increased complexity. Instead, it was suggested as a decoder-only option.

### Lossless

Most early JPEG research efforts went into the development of the higher compression (lossy) mode. However, lossless coding was essential to certain applications, as was a JPEG requirement.

Even though integer DCT would have provided the first choice, straightforward differential pulse code modulation (DPCM) was chosen by JPEG for the lossless mode. DPCM is applied in the pixel domain, where the value of a given pixel in a given color component is represented by the difference between the true value and a predicted value, and then compressed with a straightforward entropy coding technique (Huffman). Seven DPCM predictors are defined in the standard.

*Figure 6. The JPEG logo. The ISO/IEC-ITU JPEG image compression standard is celebrating its 25th anniversary of approval. Throughout the years, other milestones of the standard have been celebrated at various events, such as at EPFL, Lausanne, Switzerland in 2013 and at a town-hall of Cesson-Sévigné, Rennes, France in 2014 and at the cultural center of Saint-Malo, France and at the University of Leipzig, Germany in 2016.*

With real-life images, the compression can vary substantially (25–30 percent) with the choice of predictor. Typical compression factors between 2 and 3 can be obtained, depending on the complexity of the image and, notably, the pixel noise in the image. JPEG LS, based on the LOCO-I algorithm, was standardized with Huffman coding in 1999 and with extensions such as arithmetic coding in 2003. JPEG LS can typically give compression factors better than four.

At its creation, the goal of JPEG was a common compression scheme able to handle bi-level, halftone, and natural images. However, following the subjective testing of images, it was agreed that bi-level and halftone images would need a specific compression scheme. That gave birth to the Joint Bi-level Image Group (JBIG) in 1988, which resulted in ITU-T Recommendations ITU-T.82 (1993) and T.88 (2000). Later, the JPEG2000 project also fulfilled this "original" (but given up) JPEG requirement.

The ISO/IEC-ITU JPEG image compression standard is celebrating the 25th anniversary of the approval of the JPEG standard (see Figure 6). JPEG was the first international standard adopted for compression of natural tone digital images.[12] It is remarkable, even to those involved in its creation, that the compression technique has shown such resilience, providing the foundation for future extensions of JPEG, including JPEG2000, JPEG XT, and High Efficiency Video Coding (HEVC)-intra. **MM**

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