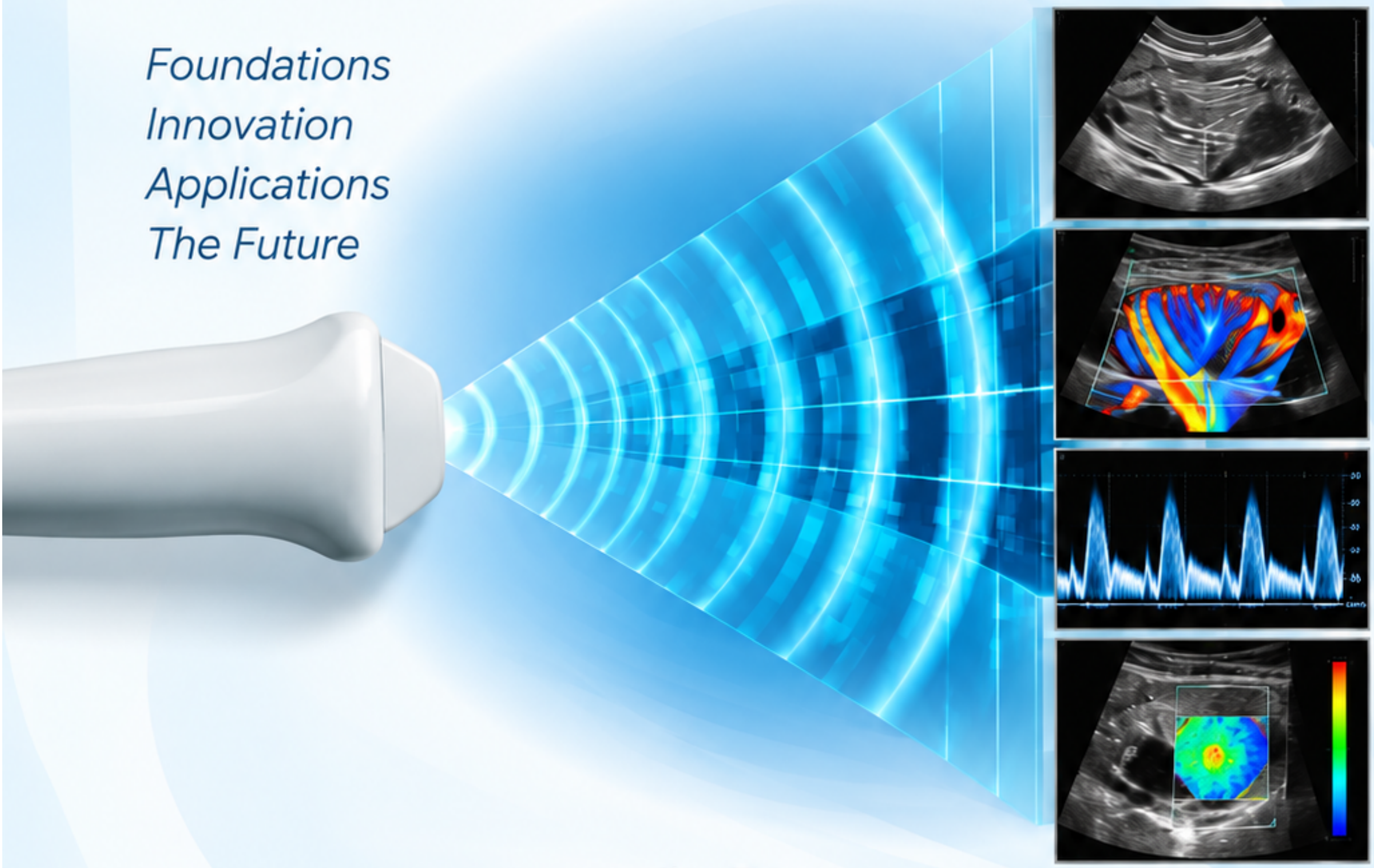
# Advances in Ultrasound Imaging Architecture

## A White Paper for Sonography Educators and Practitioners

*Foundations*
*Innovation*
*Applications*
*The Future*



**Jim Baun**

**2026**

**SonoScholar Publications**
Educational Materials for Sonographers by a Sonographer

# Advances in Ultrasound Imaging Architecture

## Rethinking the Image Creation Chain

Jim Baun, MEd, RDMS, RVT, FSDMS


## Abstract

Ultrasound imaging architecture refers to the underlying engineering design through which transmitted acoustic energy is generated, returning acoustic information is acquired and processed, and diagnostic images are ultimately constructed. Although the basic principles of pulse-echo imaging remain unchanged, the technological architecture used to implement those principles has evolved considerably.

Traditional descriptions of ultrasound image formation emphasize focused beam transmission, sequential acquisition of acoustic lines, receiver processing, scan conversion, and line-by-line frame construction. These concepts remain fundamental to understanding ultrasound physics. However, contemporary systems increasingly supplement or replace portions of this conventional architecture with broad-field transmission, software-based beamforming, acquisition of substantially larger acoustic data sets, enhanced digital signal processing, and computational reconstruction of image frames.

A useful way to understand this evolution is to view ultrasound image formation as an image creation chain composed of four interconnected architectural pillars: beamforming, acoustic acquisition, data processing, and frame construction. Examining each pillar provides a framework for comparing conventional imaging methods with emerging architectural approaches and for understanding how these changes influence system performance, advanced imaging capabilities, and sonography education.


## Introduction

Ultrasound technology has advanced dramatically since the introduction of early real-time imaging systems. Transducer design, computer hardware, digital electronics, processing speed, data storage, graphics capabilities, and software have all evolved. These advances have expanded the diagnostic capabilities of ultrasound while simultaneously changing many of the engineering processes through which images are created.

The physical principles underlying diagnostic ultrasound have not changed. Acoustic waves are transmitted into tissue, interact with tissue interfaces and scatterers, and return information to the transducer. What has changed is the manner in which the system transmits, acquires, processes, and organizes that information.

Traditional sonography education generally describes image creation as a sequential process. A focused acoustic beam is transmitted along an individual scan line. Returning echoes are received and processed. The beam is redirected, another line is acquired, and the process is repeated until sufficient lines have been collected to construct an image frame. The next frame is then created in the same manner.

That model remains important because it explains many basic relationships involving focusing, line density, imaging depth, pulse repetition frequency, temporal resolution, and spatial resolution. However, it no longer describes the complete architecture of many contemporary systems.

Newer architectures can acquire substantially larger regions of acoustic information during each transmission, preserve greater portions of the received acoustic data set, and use high-speed software algorithms to perform operations that historically depended more heavily on front-end hardware. Image formation therefore becomes increasingly computational.

For educational purposes, these changes can be organized into four components of an ultrasound image creation chain: beamforming, acoustic acquisition, data processing, and frame construction. Each represents a function that must occur regardless of the specific architectural method employed. What differs between conventional and emerging systems is how each function is accomplished.

## The Image Creation Chain

An ultrasound image does not arise from a single technological process. It represents the final product of a sequence of interdependent operations beginning with acoustic transmission and ending with construction and display of image information.

The four-pillar model provides a useful conceptual framework.

- **Beamforming —** determines how acoustic energy is transmitted into tissue and how returning acoustic information is spatially localized.
- **Acoustic acquisition —** determines how returning signals are detected, conditioned, digitized, and retained as an acoustic data set.
- **Data processing —** determines how those acquired data are analyzed, modified, combined, segmented, or otherwise transformed into diagnostically useful information.
- **Frame construction —** determines how processed information is spatially organized into an image that can be displayed and interpreted.

Conventional and emerging architectures perform all four functions. The principal difference lies in where and when many of these operations occur and in the amount of acoustic information available to the system during image creation.

## Pillar 1: Beamforming

### Conventional Beamforming

Conventional ultrasound beamforming relies heavily on carefully controlled timing relationships among individual transducer elements. During transmission, small timing differences determine when individual elements within the active aperture are excited. These delays shape the transmitted wavefront and allow the beam to be focused, steered, or otherwise modified. Receive beamforming uses corresponding timing relationships to account for differences in the arrival time of echoes returning from a particular spatial location. Signals received by multiple elements can then be combined to reinforce information originating from the intended region.

Multiple transmissions are typically required to interrogate the complete field of view. The active aperture may vary with depth, transmit focal zones may be placed at selected locations, and individual acoustic lines are sequentially created. This approach produces high-quality diagnostic images but introduces familiar tradeoffs. Increasing the number of scan lines or focal zones requires additional transmissions. Increasing imaging depth increases the time required before another pulse can be transmitted. These relationships contribute directly to limitations in temporal resolution.

### Emerging and Virtual Beamforming

Emerging architectures shift a greater portion of beamforming from fixed front-end transmission sequences to computational processing. Instead of requiring a narrowly focused transmit beam for each individual image line, the system may transmit a broad, weakly focused, unfocused, or plane-wave acoustic field capable of insonating a larger region during a single transmission. Returning signals are acquired across multiple transducer elements and retained as a much larger acoustic data set. Software algorithms can then apply spatial and temporal relationships within those data to reconstruct information originating from many locations within the insonated field. In this sense, portions of focusing and beam formation can be performed computationally after acoustic acquisition. Depending on system design, multiple broad-field transmissions may also be combined to improve spatial resolution, contrast, signal-to-noise characteristics, or image uniformity.

Synthetic aperture and related computational imaging methods represent important examples of this broader architectural concept. The significant change is therefore not the elimination of beamforming. Rather, it is a shift from beam formation that occurs predominantly through predetermined transmit events toward beam formation in which software and retrospective computation assume a larger role.

## Pillar 2: Acoustic Acquisition

### Conventional Acoustic Acquisition

After an acoustic pulse interacts with tissue, returning signals must be converted into electrical information and prepared for subsequent image formation. In the conventional model, the receiver performs several familiar functions. These include amplification, compensation for depth-dependent attenuation, rejection of unwanted low-level signals, dynamic range compression, demodulation, and frequency-dependent processing. These receiver operations convert the extremely large range of returning signal amplitudes into a form suitable for further processing and display. Historically, much of this processing occurred early in the image creation chain. Once signals were conditioned, combined, reduced, or otherwise transformed, portions of the original acoustic information were no longer independently available for subsequent processing.

### Expanded Acoustic Data Acquisition

Contemporary digital architecture permits considerably larger quantities of received acoustic information to be digitized, transferred, processed, and temporarily or permanently retained. This concept is sometimes described using the term *big data*. In this context, the term does not represent a specific ultrasound modality. Rather, it describes the increasing volume, velocity, variety, and complexity of digital acoustic information available to the imaging system.

- **Volume —** the quantity of acquired information
- **Velocity —** the speed at which the information is generated and processed
- **Variety —** the different forms and characteristics of the acquired data
- **Veracity —** the reliability and quality of the information

Preservation of a larger acoustic data set provides greater flexibility later in the image creation chain. Instead of committing the acquired information immediately to a single image representation, the system can retain information that may subsequently be processed in different ways for different diagnostic purposes. The important architectural change is therefore not simply that contemporary systems generate more data. It is that more of the acquired acoustic information can remain available for computational analysis.

## Pillar 3: Data Processing

### Conventional Processing and Scan Conversion

In conventional ultrasound architecture, signal processing prepares acquired echo information for image display. One important step is scan conversion. Acoustic information is initially collected according to the geometry of the ultrasound beam and transducer. A sector, curved-array, or linear-array transducer produces data with its own spatial organization. The scan converter transforms these data into a format appropriate for display on a rectangular image matrix.

Traditional processing also includes functions such as filtering, smoothing, edge enhancement, persistence, grayscale mapping, and other operations designed to optimize image appearance. Much of the final image therefore represents information that has already passed through several stages of processing and reduction.

### Enhanced Digital Signal Processing

Contemporary systems use substantially greater computational power to analyze acoustic information before final image presentation. High-speed digital processing allows algorithms to operate on larger data sets and to perform multiple calculations on the same acquired information. Processing can occur rapidly enough to contribute to ongoing real-time examination while also permitting selected operations to be performed retrospectively.

Individual components of the acquired acoustic data set can be characterized according to properties such as spatial position, amplitude, frequency content, phase, temporal behavior, and motion. Software can then group or segment data according to characteristics relevant to a particular imaging application. This architectural flexibility allows the same underlying acoustic information to contribute to multiple forms of image generation and quantitative analysis.

Digital signal processing is also fundamental to many advanced ultrasound applications, including sophisticated Doppler methods, elastography, contrast-enhanced imaging, motion tracking, volumetric reconstruction, automated measurements, and artificial intelligence-assisted analysis. The evolution of ultrasound architecture is therefore increasingly characterized by a transition from systems in which image formation was determined primarily by dedicated hardware toward systems in which software plays an increasingly important role in determining how acquired acoustic information is interpreted and displayed.

## Pillar 4: Frame Construction

### Conventional Line-by-Line Frame Creation

Conventional pulse-echo imaging creates an image frame by assembling information obtained from sequential acoustic lines. A beam is transmitted along one path, echoes are received, and information from that transmit-receive sequence contributes to an individual line of the image. The beam is then redirected and the process repeated. When all required lines have been acquired, the frame is complete. Because individual lines are acquired at slightly different times, the displayed frame does not represent a single instantaneous acquisition. Instead, it is a composite constructed from sequential events occurring during the frame acquisition interval. This line-by-line model explains the traditional relationship between line density, imaging depth, focal zones, field of view, and frame rate.

### Computational Frame Construction

Emerging architectures can separate frame construction from the sequential acquisition of individual conventional scan lines. When a broad region is insonated and the resulting acoustic information is preserved, software can determine where individual components of that information belong within a computational image matrix. Rather than treating the acoustic line as the fundamental building block of every image, the system can reconstruct information at much smaller spatial units within a digital scaffold. This process can be conceptualized as data-point-by-data-point or bit-by-bit frame construction.

A computational scaffold defines the spatial organization of the eventual image. Processed acoustic information is then assigned to appropriate locations within that structure according to the reconstruction algorithm being used. Multiple forms of information may be derived from the same or closely related acoustic acquisitions. Grayscale, flow, motion, elasticity, contrast, or other quantitative information can therefore be reconstructed, compared, or overlaid computationally. This approach also facilitates analysis of changes occurring among sequential reconstructed data sets, providing the foundation for applications involving motion tracking, vector-based flow assessment, and other temporal-domain analyses.

**Key distinction:** Conventional architecture acquires the image largely as a sequence of acoustic lines. Emerging architecture increasingly acquires acoustic information first and constructs the image computationally afterward.

## Why Architectural Change Matters

The significance of these developments extends beyond improvements in image appearance.

Changes within the four pillars alter what information becomes available to the ultrasound system and what can subsequently be done with it.

- more efficient acquisition of large insonated regions
- improved temporal sampling
- increased flexibility in focusing and reconstruction
- greater uniformity throughout the image field
- preservation of acoustic information for additional processing
- simultaneous or near-simultaneous generation of multiple diagnostic data types
- retrospective reconstruction or analysis
- improved quantitative assessment
- advanced Doppler and flow characterization
- volumetric and motion-based imaging
- artificial intelligence-assisted processing and interpretation
- development of increasingly software-defined ultrasound platforms

These capabilities are also relevant to emerging hardware configurations. Handheld ultrasound, highly integrated transducer electronics, microfabricated transducers, wearable ultrasound devices, and other developing technologies increasingly depend upon sophisticated computational architecture to compensate for limitations in conventional hardware or to enable new methods of data acquisition. The boundaries between transducer, beamformer, receiver, processor, and scan converter consequently become less distinct than they were in earlier generations of ultrasound equipment.

## Implications for Sonography Education

The evolution of ultrasound architecture presents an important challenge for sonography education. Traditional ultrasound physics remains essential. Sonographers must continue to understand acoustic propagation, pulse-echo principles, attenuation, resolution, transducer operation, Doppler physics, focusing, pulse repetition frequency, and the relationships among imaging parameters.

The educational issue is not that these principles have become obsolete. Rather, the technological methods used to apply them have expanded. A curriculum that describes all contemporary ultrasound systems exclusively in terms of narrowly focused transmit beams, sequential acoustic lines, conventional receiver processing, scan conversion, and line-by-line frame formation risks presenting students with an incomplete model of current technology.

A more contemporary approach can retain the traditional model while placing it within the larger image creation chain. Students can first learn how each architectural function is accomplished conventionally and then examine how newer systems accomplish the same function differently. Such an approach preserves the foundational physics while providing a framework capable of accommodating continued technological change. It also shifts the educational emphasis from memorizing the components of a particular generation of ultrasound machine toward understanding the functions that must occur during image creation.

- **Beamforming must occur.**
- **Acoustic information must be acquired.**
- **Data must be processed.**
- **An image or other diagnostic output must be constructed.**

The architecture used to accomplish those functions will continue to evolve.

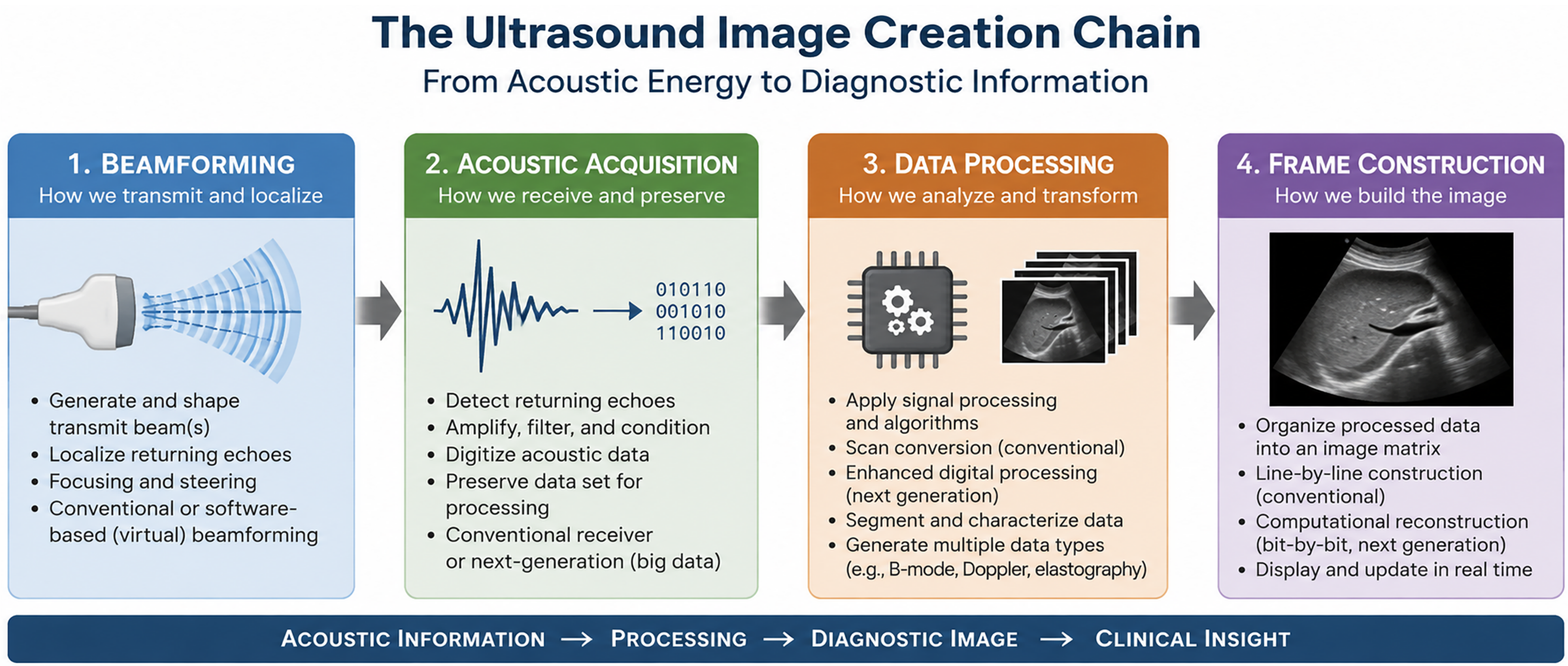
## Conclusion

Advances in ultrasound imaging architecture represent more than incremental improvements in conventional ultrasound equipment. Increasingly, they reflect changes in the fundamental organization of the image creation process. The four-pillar framework of beamforming, acoustic acquisition, data processing, and frame construction provides a useful way to understand this evolution.

Conventional ultrasound architecture relies heavily on predetermined transmit focusing, sequential acoustic acquisition, early receiver processing, scan conversion, and line-by-line image formation. Emerging architectures increasingly employ broad-field acquisition, software-based beamforming, preservation of larger acoustic data sets, enhanced digital signal processing, and computational reconstruction. These approaches should not be viewed as completely separate generations of ultrasound technology. Contemporary platforms commonly incorporate elements of both. The transition is evolutionary rather than absolute, and specific implementations vary among manufacturers and imaging applications.

Nevertheless, the direction of technological development is increasingly clear: ultrasound imaging is becoming more computational, more software-defined, and less dependent upon acquiring the final image in the same form in which it will ultimately be displayed. For sonographers and sonography educators, understanding this architectural transition is becoming an important extension of traditional ultrasound physics.

**The principles of ultrasound have not changed.**
**The way those principles are engineered into an imaging system has.**



The Ultrasound Image Creation Chain
From Acoustic Energy to Diagnostic Information
1. Beamforming
How we transmit and localize
• Generate and shape transmit beam(s)
• Localize returning echoes
• Focusing and steering
• Conventional or software-based (virtual) beamforming
2. Acoustic Acquisition
How we receive and preserve
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• Detect returning echoes
• Amplify, filter, and condition
• Digitize acoustic data
• Preserve data set for processing
• Conventional receiver or next-generation (big data)
3. Data Processing
How we analyze and transform
• Apply signal processing and algorithms
• Scan conversion (conventional)
• Enhanced digital processing (next generation)
• Segment and characterize data
• Generate multiple data types (e.g., B-mode, Doppler, elastography)
4. Frame Construction
How we build the image
• Organize processed data into an image matrix
• Line-by-line construction (conventional)
• Computational reconstruction (bit-by-bit, next generation)
• Display and update in real time
Acoustic Information → Processing → Diagnostic Image → Clinical Insight