A TECHNOLOGICAL AND INTELLECTUAL HISTORY

History of Technical Diagnostics, Observability, and Debugging

From proof testing, strain measurement, and failure analysis to nondestructive evaluation, structural health monitoring, digital twins, and AI-assisted prognosis

— evidence, causality, and the changing craft of explanation —

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Historical synthesis with 103 references, chronology, glossary, and evidence taxonomy

Abstract

Technical systems rarely announce the mechanism of their own deterioration. A hot bearing, a cracked weld, a drifting pressure boundary, or a changing bridge mode presents an effect; diagnosis must establish what changed, where it changed, why it changed, and what the evidence permits an engineer to do next. This history follows the practices that made the condition and structural integrity of physical assets increasingly observable.

Its scope follows the Handbook of Technical Diagnostics: structures, systems, components, functional performance, and structural integrity; the physics of failure; stress, strain, vibration, acoustic emission, thermography, radiology, computed tomography, embedded sensors, and microanalysis; failure analysis and machinery diagnostics; structural-health monitoring of buildings, bridges, pipelines, power stations, offshore wind turbines, and railways; and technical examination in the arts and cultural heritage [1]. Computing hardware appears only where it mediates these physical measurements, leaving electronic and computer-device diagnosis to the companion hardware history.

The central argument is that technical diagnostics did not grow as a single invention. It emerged from the convergence of inspection, mechanics, metrology, materials science, maintenance, signal processing, and institutional learning. Each new instrument widened the observable surface, but also introduced calibration, coverage, interpretation, and governance problems. The enduring craft is therefore evidential: preserve context, qualify the observation path, combine independent modalities, test causal hypotheses, and state uncertainty before intervention.

How to read this history

This article is a historical synthesis rather than a catalogue of products. Dates identify documented instruments, publications, standards, investigations, and institutional changes; they do not imply that adoption was immediate or uniform. Older practices survive inside newer systems: the walk-around inspection, witness mark, tap test, baseline trace, teardown, and maintenance log remain useful because they answer questions that automated monitoring can miss.

The term technical diagnostics is used here in the engineering sense established by the Springer handbook: diagnosis of physical structures and systems through evidence about functional performance and integrity [1]. Nondestructive testing asks whether a detectable discontinuity or property variation is present; condition monitoring asks how measured condition changes with time; failure analysis reconstructs a mechanism after damage; structural-health monitoring makes these questions persistent at asset scale; prognosis estimates future condition under explicit assumptions.

References in square brackets point to the source list. Primary standards, official investigations, archival records, and peer-reviewed work are preferred. A citation supports the historical or technical claim near it, not every interpretive sentence in a paragraph. The chronology is selective, the glossary uses working definitions, and the evidence taxonomy is designed for investigations in which several imperfect observations must be reconciled.

Neighboring practices and their primary questions

Table 1. Working distinctions used throughout this article; practices overlap in real investigations.

Practice	Primary question	Characteristic evidence
Inspection and proof testing	Does the item meet an acceptance criterion now?	Direct observation, dimensions, load or pressure response, witness records
NDE / NDT	Is a relevant discontinuity or material variation detectable without impairing use?	Indications, images, waveforms, calibration blocks, probability-of-detection evidence
Condition monitoring	Is operating condition departing from a qualified baseline?	Trends, spectra, process variables, alarms, operating-state context
Technical diagnostics	What fault, damage mechanism, or state best explains the observations?	Correlated symptoms, residuals, causal tests, competing hypotheses
Failure analysis	How and why did damage or failure occur?	Fracture surfaces, microstructure, chemistry, loads, sequence and provenance
Structural-health monitoring	Has an asset-scale structure changed, where, and with what consequence?	Distributed sensors, modal or strain fields, environmental normalization, models
Prognostics / PHM	How will condition evolve, and when will intervention be required?	Degradation models, uncertainty bounds, remaining-useful-life estimates, decisions

SEVEN RECURRING TRANSITIONS

- Sensory signs → quantified physical variables
- One-time proof tests → repeated condition histories
- Surface indications → volumetric and microstructural evidence
- Failure after the fact → damage detection before loss of function
- Single readings → multimodal, model-conditioned interpretation
- Local inspection records → asset, fleet, and lifecycle evidence
- Expert pattern recognition → auditable model- and AI-assisted diagnosis

Contents

Seven parts · 35 chapters · three reference appendices

Table 2. Article contents and opening pages.

PART I

Foundations: making condition and integrity knowable

1. Vocabulary, scope, and historical method

Technical diagnostics begins where a symptom ceases to be self-explanatory. A stain may mark an active leak, an old repair, or harmless residue; a vibration peak may indicate unbalance, resonance, looseness, or a changing operating point. The task is to infer a defensible state of a physical structure or system from observations whose sensitivity and coverage are limited. The Springer handbook organizes that task around failure physics, diagnostic methods, failure analysis, machinery, structural-health monitoring, and cultural heritage [1].

A useful evidential sequence is indication → feature → anomaly → fault or damage state → mechanism → consequence. An indication is instrument output; a feature is a measured property extracted from it; an anomaly is a departure from an expected population or baseline; a diagnosis identifies the state and causal explanation that best accounts for the evidence. Collapsing these levels invites category errors—for example, treating a hot spot as proof of delamination or a classifier label as a mechanism.

The word debugging belongs here only by analogy. Engineers have long debugged physical systems by isolating sections, substituting components, varying load, reproducing symptoms, and observing response. Yet physical intervention can erase evidence or worsen damage. Historical method therefore matters: names and instruments change, but the recurring questions are coverage, baseline, calibration, causal discrimination, and whether an observation is strong enough to justify action.

2. Craft inspection, proof testing, indicators, and records

Before formal diagnostic disciplines, builders and operators learned from sight, sound, touch, smell, deformation, leakage, and breakage. They tapped wheels and castings, watched bearing color and lubricant, gauged clearances, proof-loaded chains and bridges, and compared the behavior of similar objects. Galileo's 1638 treatment of the strength and fracture of beams helped move such craft questions into mathematical mechanics, although centuries of practical judgment remained indispensable [2].

The steam engine made hidden performance economically important. James Watt's indicator converted cylinder pressure over piston travel into a diagram, letting engineers distinguish valve timing, leakage, condensation, and load effects rather than merely observe poor output. Preserved instruments show how a transient process became a trace that could be compared across cycles and machines [3]. The diagram was an early diagnostic narrative: state, timing, loss, and mechanism compressed into shape.

Records extended observation through time. Boiler logbooks, railway defect books, ship surveys, and factory maintenance cards preserved recurrent symptoms, interventions, and outcomes. Their limitations are equally historical: terminology drifted, normal conditions were omitted, and repaired items disappeared from the failure population. Technical diagnosis became more reliable when the asset's identity, configuration, operating state, and prior work accompanied the measurement.

3. Strength of materials and the localization of stress

The history of strength of materials supplied a language for invisible internal action. From beam bending and elasticity to stress concentration and energy methods, engineers learned to relate external loads and geometry to internal stress and deformation. Timoshenko's historical survey documents how theory, laboratory testing, and structural practice repeatedly corrected one another [4]. Diagnosis could now ask not only where an object had broken, but where a design or load path made damage likely.

This was a profound shift in observability. A crack at a hole or sharp corner is local, while nominal stress is an average; a structure may satisfy a global load calculation yet contain a severe local field. Models became maps of diagnostic attention, directing inspection toward joints, notches, weld toes, interfaces, and load-transfer details. Conversely, measured strain could test whether the assumed boundary conditions and load paths were real.

The model–measurement relationship was never one-way. Proof loads exposed unexpected flexibility; deflection surveys revealed settlement or connection slip; fractured parts showed loads that design drawings did not record. Mature technical diagnostics treats the model as a hypothesis-bearing instrument. Agreement supports a particular description of the asset; disagreement may indicate damage, but can also expose an incorrect model, geometry, material property, or operating assumption.

4. Metrology, gauges, tolerances, and traceability

Industrial interchangeability made comparison a system requirement. Standard dimensions, reference artifacts, calibrated gauges, and documented tolerances allowed measurements made at different workshops and times to mean the same thing. The 1875 Metre Convention created an international institutional basis for measurement uniformity and ultimately for the traceability chains on which modern diagnostic claims depend [5].

A diagnostic instrument does not simply reveal a property; it realizes a measurement under defined conditions. Resolution, sensitivity, repeatability, bias, drift, bandwidth, alignment, surface preparation, and environmental compensation shape the result. A reading outside tolerance can therefore describe the asset, the instrument, the setup, or their interaction. Calibration checks and reference standards make the observation path itself observable.

Tolerances also changed the meaning of defect. A discontinuity is not automatically unacceptable, and a dimension is not meaningful without function, uncertainty, and decision limits. Technical diagnosis inherited this separation between measurement and disposition: first characterize what is present, then evaluate it against a code, damage-tolerance analysis, fitness-for-service rule, or risk model. That separation protects evidence from being bent toward a desired acceptance decision.

5. Boiler explosions, inspection law, and diagnostic institutions

Nineteenth-century steam power made failures public, recurrent, and catastrophic. Boiler explosions exposed weak materials, poor riveting, corrosion, unsafe pressure, inadequate water level, and organizational indifference. They also demonstrated that isolated craft knowledge was insufficient when equipment populations grew. Inspection associations, insurers, public authorities, and engineering societies began turning failure experience into rules, qualifications, and recurring examinations.

ASME traces the Boiler and Pressure Vessel Code to a 1911 initiative and the first edition to 1914–1915, following decades in which boiler disasters drove demands for uniform construction and inspection [6]. Its broader history of harnessing steam shows how tests, design margins, materials requirements, and authorized inspection became coupled [7]. The diagnostic object was no longer only the damaged plate or leaking joint; it was the entire assurance system.

This institutionalization created a pattern repeated across aviation, nuclear power, pipelines, rail, and civil infrastructure. A major failure produces investigation, mechanism knowledge, inspection requirements, record systems, and revised design rules. Yet codification can freeze assumptions. Effective diagnostics therefore uses standards as accumulated experience while remaining alert to new materials, inaccessible details, changing loads, and degradation mechanisms outside the original envelope.

PART II

Failure physics and the measured response

6. Fatigue: from railway axles to cumulative damage

Repeated loads made service history diagnostically decisive. August Wöhler's systematic railway-axle experiments in the nineteenth century related stress amplitude and cycles to failure, creating the lineage of S–N curves and endurance testing [8]. A component could survive a proof load yet fail under smaller repeated loads; inspection therefore had to search for initiated cracks and maintenance had to count or estimate cycles.

Griffith's energy treatment of brittle fracture showed in 1921 why small flaws could control macroscopic strength [9]. Miner's 1945 cumulative-damage rule later offered a simple way to combine variable-amplitude fatigue exposure [10]. Both were powerful abstractions and diagnostic cautions: real structures contain residual stress, sequence effects, environments, manufacturing variability, and load spectra that a single scalar damage fraction cannot preserve.

Fatigue diagnosis grew into a chain: reconstruct loads, identify stress raisers, characterize crack initiation sites, measure crack size and orientation, estimate growth, and compare the remaining ligament with critical conditions. Each link carries uncertainty. A missing crack indication can mean no crack, poor access, insufficient sensitivity, unfavorable orientation, or a flaw below threshold; the inspection interval must therefore be tied to both crack-growth physics and demonstrated detection capability.

7. Fracture mechanics: critical flaws, crack growth, and damage tolerance

Fracture mechanics converted cracks from categorical defects into measurable states. Irwin's stress-intensity formulation related crack geometry and loading to the near-tip field [11]. Paris and Erdogan's 1963 crack-growth relation connected stress-intensity range to fatigue-crack advance [12]. Together with toughness testing, these ideas supported damage tolerance: assume flaws may exist, detect them before they become critical, and schedule inspection against growth.

This logic changed what an NDE result needed to contain. Location alone was insufficient; length, depth, orientation, ligament, uncertainty, and relation to the stress field mattered. The same indicated size could be benign in compression and dangerous at a tensile hot spot. Qualification specimens, sizing error studies, and conservative evaluation rules grew because diagnosis had to support an engineering consequence, not merely recognition.

Fracture surfaces also became historical records. Beach marks, striations, cleavage facets, ductile dimples, origin features, corrosion products, and arrest lines can reconstruct initiation and propagation—provided the surfaces are protected from handling and oxidation. Fracture mechanics and fractography are complementary: the model predicts what loading can do; the surface records what a particular component experienced.

8. Creep, corrosion, wear, and interacting degradation

Not all damage is crack growth under counted cycles. Weibull's statistical treatment of strength helped formalize population variability and weakest-link behavior [13]. Larson and Miller's time–temperature parameter offered a practical way to organize creep-rupture data [14]. Such tools made exposure history—temperature, time, atmosphere, stress, and manufacturing lot—part of diagnosis rather than background detail.

Wear and corrosion made interfaces and environments central. Archard's wear relation connected wear volume with load, sliding distance, hardness, and an empirical coefficient, while tribology developed richer accounts of lubrication, debris, surface fatigue, and scuffing [15]. The corrosion profession institutionalized shared evidence; NACE, now part of AMPP, traces its origin to pipeline corrosion engineers in 1943 [16].

Real failures couple mechanisms: corrosion pits initiate fatigue cracks; overheating changes microstructure and accelerates creep; poor lubrication raises temperature and vibration; fretting creates debris and false indications. Physics-of-failure approaches therefore model stresses and mechanisms rather than extrapolating a generic failure rate [17]. Multimodal evidence is strongest when each modality observes a different link—environment, material state, damage geometry, and functional response.

9. Reliability, FMEA, fault trees, and risk-based inspection

Twentieth-century reliability engineering shifted attention from individual breakdowns to populations and systems. The familiar bathtub curve organized early failures, approximately random useful life, and wear-out, while also inviting misuse when heterogeneous mechanisms were forced into one shape [18]. Failure-mode and effects analysis made teams enumerate how components could fail and what each failure would do; MIL-STD-1629A codified a widely influential procedure [19].

Fault trees reversed the direction of reasoning: begin with an undesired top event and decompose combinations of contributing events. NASA's handbook emphasizes both the analytical structure and the discipline required to define boundaries and assumptions [20]. These methods made diagnostic coverage visible—what symptoms, tests, or protections could detect each path—and exposed common-cause failures that simple redundancy counts concealed.

Risk-based inspection joined probability and consequence to allocate finite inspection effort. API RP 580 frames programs for pressure-containing equipment around systematic risk assessment rather than uniform intervals [21]. The gain is prioritization; the hazard is false precision. A risk model inherits uncertain degradation rates, inspection effectiveness, consequence models, and missing mechanisms. Its outputs should guide inquiry, not substitute for field evidence or engineering judgment.

10. Measuring strain: extensometers, bonded gauges, photoelasticity, and DIC

Strain measurement turned deformation into local evidence about load path. Mechanical extensometers and resistance-based devices evolved into bonded electrical strain gauges; historical reviews trace the lineage from early resistance observations to modern optical and distributed sensors [22]. Edward E. Simmons began related resistance-wire work in 1936 and patented his design in 1940; Arthur C. Ruge developed a bonded resistance gauge in 1938, and their work was later covered jointly by a 1944 patent [23].

Photoelasticity provided a different kind of observability. Polarized-light fringe patterns on transparent models made whole-field stress differences visible, and Coker and Filon's 1931 treatise consolidated an experimental tradition that influenced design around holes, fillets, and contacts [24]. Its lesson survives in modern fields: spatial context can reveal a mechanism that a single sensor at a nominal location misses.

Digital image correlation later estimated displacement and strain by tracking surface texture across images, extending whole-field measurement to real materials, large deformations, and dynamic tests [25]. Yet the apparent field depends on optics, calibration, subset size, lighting, surface preparation, and out-of-plane motion. Whether using a bonded gauge or a camera, diagnostic meaning requires a coordinate system, load history, thermal compensation, uncertainty, and a defensible baseline.

11. Vibration and modal diagnosis: from resonance to operational evidence

Vibration carries information about stiffness, mass, damping, forcing, clearances, and rotating geometry. Rayleigh's nineteenth-century Theory of Sound helped unify vibration and wave phenomena [26]. With electrical transducers and analyzers, engineers could record motion rather than rely on touch or audible tone; with Cooley and Tukey's 1965 fast Fourier transform, routine spectral analysis became computationally practical [27].

Machine diagnosis learned to distinguish shaft speed, harmonics, sidebands, bearing defect frequencies, resonances, and transients. Standards such as ISO 20816 organize measurement and evaluation of machine vibration, but severity zones are not universal diagnoses [28]. The same amplitude can be normal at one load and alarming at another; phase, direction, speed, process state, and trend often carry more causal information than a single overall value.

Modal testing measures a structure's dynamic properties and compares shapes, frequencies, and damping across configurations. Ewins' synthesis links excitation, measurement, signal processing, and model validation [29]. Operational modal analysis later used ambient excitation when controlled forcing was impractical. Environmental and operational variability can exceed damage-induced change, so normalization and repeated baselines are not statistical decoration—they are prerequisites for credible inference.

PART III

Nondestructive evaluation and the failure-analysis laboratory

12. Surface examination: visual, penetrant, and magnetic-particle methods

Industrial NDE grew from many trades into a profession with shared terminology, procedures, and personnel qualification. ASNT traces its institutional origin to the American Industrial Radium and X-Ray Society founded in 1941 [30]. ASTM E1316 supplies a cross-method vocabulary, an important safeguard because indication, discontinuity, defect, and flaw are not interchangeable decisions [31].

Visual testing remains the first and often widest-coverage method: direct or remote viewing, magnification, dimensional aids, lighting control, and comparison with prior condition [32]. Liquid penetrant testing evolved from oil-and-whiting practices in railway shops; fluorescent penetrants improved contrast, and Robert Switzer's patent records part of that transition [33,34]. These methods reveal surface-breaking paths but depend strongly on cleaning, dwell, geometry, developer, and interpretation.

Magnetic-particle testing makes leakage fields around surface and near-surface discontinuities visible in ferromagnetic materials [35]. It adds sensitivity but not omniscience: field direction, magnetization level, geometry, residual fields, coatings, and material permeability shape indications. Across all three methods, a photograph without scale, orientation, surface state, procedure, and acceptance basis is a weak record. The observation must preserve how the indication was produced.

13. Industrial radiography: seeing through matter

Wilhelm Röntgen's 1895 communication on X-rays rapidly created a way to observe internal structure through differential attenuation; its contemporary English translation and the later Nobel record document the discovery and its scientific significance [36,37]. Industrial radiography adapted X-ray tubes and radioactive sources to welds, castings, pressure boundaries, and assemblies. It made porosity, inclusions, lack of fusion, geometry, and hidden assembly conditions accessible without sectioning [38].

Radiographic evidence is a projection, not a transparent window. Source size, energy, distance, object thickness, orientation, scatter, detector response, and exposure determine spatial resolution and contrast. Planar flaws can disappear when aligned unfavorably, while geometry can imitate discontinuity. Image-quality indicators and technique records therefore qualify what the radiograph could have revealed.

Film created durable physical records but imposed chemical processing and limited dynamic range. Computed and digital radiography improved acquisition, enhancement, transfer, and comparison, while making provenance and processing history newly important. Digital contrast adjustment can help interpretation but can also hide saturation or create persuasive artifacts. The original data, calibration, and display conditions belong to the diagnostic record.

14. Ultrasonics: echoes, beams, and internal geometry

Pulse-echo ultrasonics transformed internal discontinuities into time-of-flight and amplitude evidence. Floyd Firestone's 1942 patent described a flaw-detecting device based on reflected high-frequency waves [39]. Later instruments, piezoelectric probes, reference blocks, angle-beam techniques, immersion scanning, phased arrays, and full-matrix capture expanded coverage and made beam steering and image reconstruction practical [40].

An ultrasonic indication is produced by an acoustic path. Coupling, surface condition, velocity, attenuation, grain structure, probe frequency, near field, beam spread, refraction, mode conversion, and flaw orientation all matter. Calibration on a convenient reflector cannot by itself prove sensitivity to a service crack with different roughness and orientation. Procedure qualification must connect the simulated target to the actual inspection problem.

Modern arrays generate intuitive sector scans and volumetric views, but the underlying evidence remains a sampled wave field. Focusing laws and reconstruction algorithms embed assumptions; dead zones and inaccessible surfaces remain. Strong diagnosis combines encoded position, raw or preservable A-scan data, scan plan, calibration checks, geometry, and independent confirmation when sizing governs structural disposition.

15. Eddy-current and electromagnetic diagnosis

Electromagnetic methods infer material and geometric change from induced fields. ASNT's electromagnetic family includes eddy current, alternating-current field measurement, remote field, magnetic-flux leakage, and related techniques [41]. Historical accounts connect practical eddy-current inspection to nineteenth-century observations by Hughes and to later impedance-plane instrumentation [42].

Eddy currents are sensitive to surface and near-surface cracks, conductivity, permeability, thickness, heat treatment, and probe lift-off. That richness is also ambiguity: several variables can move the instrument response in similar directions. Frequency selection, differential probes, reference standards, phase analysis, scanning mechanics, and knowledge of material state are how practitioners separate flaw response from geometry and lift-off.

In tubes, aircraft fastener holes, rails, wire rope, and pipelines, specialized probes trade generality for coverage. Array systems and model-based inversion can estimate shape, yet their result is conditional on electromagnetic properties and geometry. As in all diagnostics, an image that looks like a crack is not the endpoint; the claim must specify detectability, location, uncertainty, and the physical alternative explanations considered.

16. Acoustic emission: listening for active damage

Acoustic-emission testing differs from methods that interrogate a static volume: it listens for transient elastic waves produced by active processes such as crack growth, fiber breakage, friction, leakage, or corrosion. Josef Kaiser's 1950 work and the Kaiser effect became landmarks in the field's history [43]. The method promised global surveillance of large structures under load, using sparse sensors to detect activity.

Source location by arrival times, event counts, amplitude distributions, frequency content, and load correlation can distinguish active zones. But propagation through real structures adds attenuation, dispersion, reflections, and mode conversion; mechanical noise and electromagnetic interference create look-alikes. Grosse and Ohtsu's synthesis treats sensors, signal processing, source mechanisms, and structural applications as one system [44].

The method's greatest strength—sensitivity to activity—is also its boundary. Quiet does not prove absence of damage; a dormant crack may emit nothing during the test. Load history matters because prior loading can suppress emission until a previous maximum is exceeded. Acoustic emission is therefore most persuasive when combined with controlled loading, verified sensor coupling, noise characterization, location uncertainty, and targeted follow-up NDE.

17. Infrared thermography: heat flow as evidence

William Herschel's 1800 experiments identified invisible radiation beyond the red end of the spectrum [45]. Two centuries of detector, optics, and computing development turned infrared radiation into calibrated temperature fields and transient thermal movies. In maintenance, passive thermography reveals abnormal heating in bearings, electrical connections, refractory linings, insulation, and process equipment; active thermography perturbs heat flow to reveal subsurface differences.

Thermal contrast is not temperature by default. Emissivity, reflection, atmosphere, viewing angle, focus, spatial resolution, detector calibration, and transient conditions shape the image. Maldague's treatment of infrared NDT emphasizes heat-transfer physics and experimental design, especially for pulsed, lock-in, and other active techniques [46]. A bright region can be a hot defect, a reflective surface, or a different coating.

Thermography's historical contribution was whole-field, noncontact observation at operating scale. It could survey thousands of electrical joints or map delamination in a panel, but only under conditions that produced discriminating heat flow. Good records include radiometric data, visible context, environmental conditions, emissivity assumptions, load, time after excitation, and a baseline or sound comparison region.

18. Computed tomography, digital imaging, and interoperable records

Computed tomography reconstructs cross-sections from many radiographic projections, reducing superposition and enabling three-dimensional measurement of internal geometry. Industrial systems emerged in the late twentieth century and expanded from laboratory specimens to castings, composites, additive parts, and assembled mechanisms. ASTM E1441 provides guidance for imaging with industrial CT [47].

The diagnostic gain is volumetric context: pores can be segmented, cracks followed, wall thickness measured, and internal assemblies compared with nominal geometry. The tradeoffs are energy, magnification, scan time, reconstruction artifacts, material combinations, voxel size, and the difference between nominal voxel spacing and demonstrated feature detectability. De Chiffre and colleagues review this migration into industrial metrology and NDE [48].

Digital evidence also needed a durable language. ASTM E2339's DICONDE practice adapts concepts from medical imaging to nondestructive evaluation so images, metadata, technique, and specimen identity can travel together [49]. Interoperability is diagnostic infrastructure: without stable identifiers, acquisition parameters, calibration, orientation, and processing history, a sophisticated volume becomes an orphaned picture that cannot be reinterpreted or audited.

19. The failure-analysis laboratory: from fracture surface to mechanism

Failure analysis is destructive only when necessary and usually begins with preservation. Scene context, as-received photography, fracture matching, deposits, witness marks, operating records, and comparison parts can be lost through cleaning or cutting. ASM's Failure Analysis and Prevention handbook treats the investigation as a staged process linking evidence collection, testing, analysis, and corrective action [50]; Dennies emphasizes organization, questions, and chain of evidence [51].

Optical metallography, hardness, mechanical testing, SEM, EDS, X-ray diffraction, and surface analysis reveal structure at successively smaller scales. Ernst Ruska's electron-microscope work, recognized by the 1986 Nobel Prize, made fracture morphology and microstructure observable far beyond optical limits [52]. NIST's surface-analysis resources and XPS guidance show why reference data, charge correction, sampling depth, and instrument practice matter to chemical claims [53].

ASTM E2332-04 once formalized a practice for investigation and analysis of physical-component failures, but it has been withdrawn; current work should use applicable ASTM E07 standards and current ASM Handbook guidance [50,54]. The strongest explanation triangulates design, material, manufacture, environment, loading, and sequence. A single striking micrograph rarely proves root cause. Analysts must distinguish initiation from consequential damage, mechanism from organizational cause, and evidence-supported conclusions from plausible recommendations. Representative sampling and preservation of untested material keep the result revisable.

PART IV

Machines, plants, and mobile systems

20. Rotating machinery: condition monitoring becomes a system

Rotating machines made diagnosis continuous because failure modes announce themselves in motion. Shaft vibration, bearing acceleration, speed, phase, temperature, motor current, process variables, and sound form a coupled signature. ISO 17359 frames condition-monitoring programs from criticality and failure modes through measurement, analysis, and review [55]. The program—not the sensor—is the diagnostic instrument.

By the late twentieth century, portable analyzers and permanently installed systems supported route-based trending, spectral comparison, order tracking, envelope analysis, and alarm management. Jardine, Lin, and Banjevic's 2006 review connects data acquisition, processing, diagnostics, and maintenance decision-making [56]. ISO 13374 later organized the data-processing and communication functions required to move from acquisition to health information [57].

Automation introduced scale and new failure modes. Thresholds can chatter across operating states; a replaced sensor can create a false step; resampling can distort spectra; missing data can resemble normality. NIST's PHM roadmap treats measurement science, false alarms, data exchange, and validation as central obstacles [58]. A trustworthy system retains speed, load, configuration, sensor identity, waveform provenance, and the path from feature to recommendation.

21. Lubricant analysis and wear debris: the machine in its fluid

Lubricant is both working medium and evidence carrier. Viscosity, water, oxidation, additive depletion, acidity, contamination, particle count, elemental spectroscopy, and debris morphology describe lubricant health, ingress, and wear. Ferrography arranges wear particles by magnetic and size behavior so shape and composition can be interpreted in relation to rubbing, cutting, fatigue, or severe sliding; NASA bearing-fatigue tests demonstrated how ferrographic examination characterizes generated wear debris [59].

Oil analysis extends coverage to enclosed contacts that are hard to instrument directly, but samples are histories filtered by flow path, settling, filtration, top-up, and sampling practice. A clean sample after an oil change is not proof of a healthy gearbox. Trending within a consistent location and procedure is often more valuable than a universal limit, and debris findings should be correlated with vibration, temperature, inspection, and operating state.

Tribological diagnosis joins surface mechanism to system function. Archard's relation is a starting model, not a unique classifier [15]. Scuffing, micropitting, rolling-contact fatigue, corrosive wear, and contamination can overlap. Diagnostic confidence rises when particle morphology, alloy chemistry, lubricant condition, filter inspection, contact geometry, and load history tell the same causal story.

22. Pressure vessels, process plants, and pipelines

Process equipment concentrates technical-diagnostic problems: pressure boundaries, corrosive fluids, cyclic transients, insulation, welds, dead legs, supports, relief devices, and changing service. Inspection codes and API 570 programs make in-service piping examination, rating, repair, and alteration a managed lifecycle rather than a reaction to leakage [60]. Risk-based inspection further prioritizes damage mechanisms and consequences [21].

Pipelines add distance and burial. Operators combine patrols, cathodic-protection surveys, leak detection, pressure and flow histories, in-line inspection tools, hydrotests, excavation, coating assessment, and fracture analysis. Magnetic-flux leakage, ultrasonic wall measurement, and geometry tools observe different properties; tool alignment and odometer matching are required to compare runs and locate a feature on the ground.

The diagnostic challenge is data fusion across scales. A corrosion colony has local depth and length, but its meaning depends on material, pressure history, interaction rules, growth rate, coating, soil, and nearby stress concentrators. A process alarm may reveal a leak but not its cause; an in-line indication may reveal metal loss but not current activity. Integrity decisions are strongest when monitoring, inspection, material records, and excavated truth are reconciled.

23. Electric power and nuclear plants: online monitoring with defense in depth

Power stations brought diagnostics into safety, availability, and regulatory assurance. Turbines and generators use vibration, electrical, thermal, and lubricant evidence; boilers and heat exchangers use chemistry, thickness, leak, and NDE records; civil structures add settlement and cracking. Nuclear plants further distinguish safety classification, qualified instrumentation, surveillance tests, redundancy, and defense in depth.

The IAEA's 2008 guide on online monitoring covers process and component condition monitoring and diagnostics, emphasizing the use of plant signals to detect degradation while equipment remains in service [61]. Its condition-based-maintenance guidance connects technology with work selection, acceptance criteria, trending, economics, and the overall maintenance program [62]. Online data supplements rather than abolishes periodic examination and functional testing.

Instrument channels can drift, common process changes can move many signals, and maintenance can alter baselines. Diagnostic systems therefore need independent checks, configuration control, validated models, and explicit treatment of sensor faults. In high-consequence plants, a recommendation must preserve the distinction between early warning, confirmed degradation, operability, and safety disposition. The governance of evidence is part of the technical design.

24. Aerospace: full-scale testing, damage tolerance, and fleet evidence

Aircraft made low weight, repeated pressurization, inaccessible structure, and severe consequence converge. The de Havilland Comet investigations used wreckage reconstruction and full-scale pressure-cabin testing to connect fatigue cracking and structural detail with catastrophic breakup; the official inquiry remains a landmark in evidence-led redesign and test practice [63]. Aerospace certification subsequently gave fatigue, fail safety, and damage tolerance greater institutional weight.

Inspection became a fleet program: visual and detailed checks, eddy current around fasteners, ultrasonics, radiography, borescope examination, engine debris, vibration, and structural repairs recorded against aircraft identity and cycles. The Aloha Airlines Flight 243 investigation showed how multiple-site fatigue, corrosion, inspection program assumptions, and aging-aircraft operation could combine [64].

Modern vehicle-health systems add onboard sensing, central maintenance messages, exceedance recording, and prognostics. Yet flight conditions, maintenance actions, part swaps, and software configurations mediate every trace. Fleet evidence can reveal rare patterns, but only if effectivity and exposure are preserved. An alert that cannot be tied to a physical location, configuration, and maintenance outcome is weak engineering evidence.

25. Railways and vehicles: wheels, rails, bearings, and distributed fleets

Rail diagnostics began with inspection of track, wheels, axles, and hot bearings and grew into instrumented trains, wayside detectors, ultrasonic rail cars, geometry measurement, wheel-impact monitors, acoustic arrays, and onboard condition data. The wheel–rail contact is a moving fatigue experiment: load, traction, contamination, profile, grinding, metallurgy, and temperature shape damage.

The 2000 Hatfield derailment made the organizational meaning of technical evidence unmistakable. The rail fragmented after rolling-contact fatigue developed into multiple cracks; later reviews emphasized not only the mechanism but failures to manage inspection and maintenance information [65]. Detection capability, defect classification, work planning, possession access, and delivery of replacement rail formed one diagnostic chain.

Road vehicles likewise combine periodic inspection, onboard sensors, noise/vibration/harshness analysis, alignment, brake and tire measurements, fluid analysis, and fleet telematics. In both rail and road, population data can identify outliers, but route, load, weather, wheel position, maintenance, and sensor calibration must travel with the observation. The unit of diagnosis is often no longer a component; it is component–vehicle–route–maintenance history.

PART V

Structures, infrastructure, and manufacturing health

26. Buildings, bridges, dams, and the rise of structural-health monitoring

Civil structures are long-lived, exposed, heterogeneous, and rarely available for laboratory-style testing. Visual inspection, survey, crack gauges, load tests, cores, rebound and ultrasonic methods, ground-penetrating radar, impact echo, acoustic emission, and vibration each observe a different slice of condition. NIST documented NDE for installed building materials and later surveyed concrete NDT for service-life modeling [66,67].

Bridge inspection became a national system in the United States after the 1968 Federal-Aid Highway Act led to National Bridge Inspection Standards; FHWA states that the program's purpose is to locate and evaluate deficiencies [68]. The Silver Bridge collapse tied a critical, inaccessible eyebar flaw to stress corrosion and corrosion fatigue [69]. The I-35W collapse later showed that inspection cannot compensate for an unexamined design error and unmodeled gusset-plate capacity [70].

Structural-health monitoring formalized continuous or repeated inference from response data. Farrar and Worden framed SHM as statistical pattern recognition [71]; the Los Alamos review catalogued vibration-based damage identification [72]; the field's axioms emphasized environmental variability, damage locality, and feature sensitivity [73]. Daum's handbook chapter connects SHM concepts, assessment, and implementation [74], while FHWA's long-term bridge program demonstrates the value of comparable lifecycle data [75].

27. Embedded, fiber-optic, and wireless sensing

Embedded sensors changed inspection from episodic access to persistent observation. Strain, temperature, acceleration, corrosion potential, acoustic emission, displacement, and environmental variables could be recorded inside concrete, composites, machinery, or remote infrastructure. Fiber Bragg gratings grew from the 1978 discovery of photosensitivity in optical fibers and became multiplexable strain and temperature sensors [76].

Wireless sensing reduced cabling cost and enabled distributed networks. Lynch and Loh's 2006 review describes the integration of sensors, local computation, communications, and power constraints for structural monitoring [77]. Local feature extraction could save bandwidth and energy, but it also moved interpretation into nodes whose firmware, clocks, packet loss, and battery condition became part of the measurement chain.

Persistent sensing creates a new diagnostic object: the sensor system itself. Drift, debonding, moisture, cross-sensitivity, installation strain, synchronization, topology changes, and missing data can imitate structural change. Redundancy should be physical and analytical—overlapping modalities, reference sensors, self-tests, environmental measurements, and periodic independent inspection. A silent network must never be rendered as a healthy structure.

28. Offshore structures and wind turbines

Offshore assets combine difficult access, cyclic loading, corrosion, waves, wind, seabed interaction, and safety-critical machinery. Inspection divers and remotely operated vehicles examine welds, coatings, marine growth, scour, and members; topside systems contribute vibration, oil, electrical, thermal, and process evidence. Remote monitoring is attractive precisely because access is costly, but environmental variability can dominate the signals.

Wind turbines join a flexible tower and foundation with rotating drivetrain, blades, power electronics, and grid interaction. Blade thermography, ultrasonics, shearography, acoustic methods, and drone imagery target composites; drivetrain systems trend bearings, gears, lubrication, and generator behavior. ISO 16079-2 specifies implementation guidance for wind-turbine condition monitoring with particular attention to drivetrain failure modes, diagnostics, and prognostics [78].

Asset-scale diagnosis requires synchronization across structural, mechanical, meteorological, and control data. A tower-frequency shift can arise from damage, soil stiffness, temperature, rotor speed, or controller state; a gearbox alarm can follow transient torque rather than degradation. Useful systems preserve sea state or wind field, operating regime, curtailment, maintenance, sensor health, and uncertainty so remote experts can distinguish environment from mechanism.

29. Manufacturing, in-process monitoring, and additive construction

Manufacturing diagnostics historically separated final inspection from process control. Gauges and sampling accepted dimensions; NDE screened castings, forgings, welds, and bonds; destructive coupons characterized material. Statistical process control then treated variation as a process signal. In-process sensors brought melt pool, force, acoustic, vibration, power, temperature, and machine state into the quality record.

Additive manufacturing made this convergence explicit. Layerwise imaging and thermal monitoring can observe process anomalies, while CT, ultrasonics, microscopy, and mechanical tests characterize the built part. NIST IR 8538 maps in-process monitoring and NDE for metal additive processes, emphasizing the measurement and qualification gaps between a process signature and a material discontinuity [79].

The diagnostic temptation is to equate anomaly detection with part certification. A bright pixel, spatter event, recoater interruption, or unusual acoustic feature is evidence about process behavior, not automatically a rejectable flaw. Correlation requires registered coordinates, machine and material genealogy, parameter history, post-build NDE, and destructive truth. The digital thread is valuable when it preserves these transformations rather than merely accumulating data.

30. Qualification, probability of detection, laboratories, and decision thresholds

A diagnostic method becomes an engineering capability only when its performance is demonstrated for the target, geometry, material, procedure, equipment, and people. MIL-HDBK-1823A organizes NDE reliability assessment around probability of detection as a function of target size and requires control of the complete inspection system [80]. This replaces the fiction of a sharp detectable/not-detectable boundary with an empirical curve and confidence bounds.

Personnel competence is likewise part of the system. ISO 9712 specifies qualification and certification requirements across industrial NDT methods [81]. ISO/IEC 17025 addresses the competence, impartiality, and consistent operation of testing and calibration laboratories [82]. Written procedures, training specimens, vision and acuity, equipment checks, calibration, environmental controls, and audit trails are not bureaucracy around the evidence; they determine what the evidence can mean.

Thresholds trade misses against false calls. Their consequences are asymmetric and contextual: a missed crack may be catastrophic, while an excessive false-call rate can consume access, erode trust, or prompt damaging rework. Qualification should therefore report coverage, sensitivity, sizing error, reproducibility, human factors, and known blind zones. A method's confidence claim must be narrower than the conditions under which it was demonstrated.

PART VI

From physical evidence to models, prediction, and heritage

31. Technical examination in the arts and cultural heritage

The Springer handbook deliberately includes diagnostics in the arts and cultural heritage, extending the same evidential questions to paintings, sculpture, buildings, manuscripts, and archaeological objects [1]. Here the goal is not operational availability but knowledge and preservation: identify materials, construction, alterations, hidden features, deterioration, and treatment risk while minimizing sampling.

Conservators use visible examination, microscopy, ultraviolet fluorescence, infrared reflectography, X-radiography, X-ray fluorescence, spectroscopy, CT, thermography, and 3D imaging. The Smithsonian describes infrared imaging as a nondestructive way to reveal details below upper paint layers [83]. The Metropolitan Museum's study of Madame X shows scanning XRF mapping the elemental distribution of pigments and revisions [84].

Interpretation is necessarily interdisciplinary. An elemental map is not a pigment name without chemistry and art-historical context; an underdrawing is not automatically an earlier hand; a crack pattern can reflect support, ground, paint, climate, or treatment. The heritage laboratory reinforces a general principle of technical diagnosis: the least invasive sequence should answer the question first, and sampling should be targeted by preserved, spatially registered observations.

32. Signal processing, observability, model-based diagnosis, and data fusion

Digital signal processing expanded what could be extracted from waveforms: spectra, cepstra, envelopes, orders, wavelets, coherence, modal parameters, images, and change features. The FFT made many operations routine [27], but feature abundance did not resolve causality. Windowing, filtering, resampling, averaging, and normalization can create or erase evidence; raw data and processing parameters must remain traceable.

Control theory supplied a precise concept of observability: whether internal state can be inferred from available outputs under a model. Kalman's 1960 control-systems paper formalized controllability and observability [85]; his filtering paper made recursive state estimation practical [86]. Model-based diagnosis later represented components, expected behavior, and conflicts; Reiter's 1987 theory formalized diagnosis as sets of assumptions whose failure can explain observations [87].

Data fusion combines modalities at signal, feature, or decision level. It is strongest when evidence has partly independent failure modes: vibration plus oil debris, thermography plus ultrasonics, strain plus load and temperature, or process monitoring plus CT. ISO 13379 codifies contemporary guidance for data interpretation and machine diagnosis [88]. Fusion should preserve disagreement, not average it away; conflicting sensors may identify an observation-path fault or an unmodeled operating regime.

33. Prognostics, digital twins, and AI-assisted diagnosis

Prognostics estimates future condition and remaining useful life rather than merely naming present state. NASA's Prognostics Center of Excellence made run-to-failure and degradation data reusable [89], and the C-MAPSS turbofan simulation became a benchmark for multivariate RUL studies [90]. ISO 13381 now structures prognosis processes, required data, and communication of results [91]. Benchmarks enabled comparison but also encouraged optimization to simplified labels and operating regimes.

Digital twins joined continuously updated evidence with models of a particular asset. NASA's 2012 formulation described an integrated, probabilistic, multiscale simulation of an as-built vehicle or system [92]. NIST distinguishes descriptive, diagnostic, predictive, prescriptive, and intelligent twins [93], while ISO 23247 provides a manufacturing framework and reference architecture [94]. A twin is diagnostic only when its identity, configuration, data latency, model validity, and uncertainty are maintained.

Machine learning automated feature extraction and classification. Surveys by Zhao and colleagues and by Lei and colleagues chart the move from engineered features to deep and transfer learning for machine health [95,96]. The hard problems remain domain shift, rare faults, censored maintenance data, confounding operating conditions, label quality, calibration, and causal explanation. The NIST AI Risk Management Framework adds governance concepts for trustworthy use [97]. AI should rank hypotheses and evidence, not manufacture certainty; abstention, provenance, independent confirmation, and human authority belong in the design.

PART VII

Case studies, synthesis, and future directions

34. Diagnostic lessons from consequential technical failures

Wartime welded cargo ships made brittle fracture a population-scale lesson. The wartime Board of Investigation linked Liberty-ship cracking to interacting design, material, welding, stress-concentration, and crack-arrest conditions [98]. A modern metallurgical reexamination shows how surviving ship material can refine that historical evidence [99]. The Comet inquiries joined wreckage, full-scale pressure testing, fatigue, and structural detail [63]. In both, failure revealed a mechanism that proof testing and prevailing design assumptions had not adequately bounded.

Bridge and rail disasters showed that inspectability and information flow are design properties. The Silver Bridge contained a critical eyebar flaw that contemporary inspection could not readily detect [69]. I-35W failed from inadequate gusset-plate capacity under accumulated and construction loads, a condition routine inspection was not designed to discover [70]. Hatfield combined rolling-contact fatigue with failures to convert known condition into timely maintenance [65].

Complex systems add ambiguous tests and organizational pressure. Apollo 13's oxygen-tank failure demonstrated telemetry-led diagnosis and improvised recovery [100]; Challenger showed how evidence about O-ring erosion was normalized and communicated [101]; Fukushima exposed instrumentation and situational-awareness limits under extreme conditions [102]; Deepwater Horizon showed how negative-pressure test evidence could be misinterpreted before loss of well control [103]. Aloha 243 tied fleet aging, corrosion, fatigue, and inspection assumptions together [64]. Across cases, the diagnostic failure was rarely a missing sensor alone; it was a broken chain from indication to action.

35. Recurring principles and future directions

Establish a qualified baseline before interpreting deviation. Preserve asset identity, configuration, operating state, environment, location, orientation, time, calibration, and processing. Separate detection, localization, characterization, diagnosis, consequence assessment, and prognosis. Each is a different claim with different evidence. Design the observation path so its own failures—drift, dropout, saturation, misregistration, and stale models—are visible.

Combine passive monitoring with controlled tests and independent modalities. Preserve first-failure and as-found evidence before cleaning, disassembly, reset, or repair. Tie inspection intervals to degradation physics and demonstrated probability of detection, not custom alone [80]. Maintain competence, reference specimens, and laboratory traceability [81,82]. Close the loop from field findings to design, manufacturing, access, repair criteria, and training.

The next frontier is not simply more sensors or larger models. Distributed fiber, autonomous scanning, robotic access, edge analysis, physics-informed learning, and digital twins will widen coverage, but they also widen the surface for silent error. Future systems should express uncertainty, detect domain shift, preserve raw evidence, simulate alternative mechanisms, and abstain when conditions exceed qualification. The final explanation must remain physical, causal, and actionable—even when AI helped find it [97].

Conclusion

The history of technical diagnostics is a history of disciplined inference about physical things. Craft inspection made symptoms shareable; mechanics made hidden stresses calculable; metrology made observations comparable; NDE extended sight below surfaces; failure analysis connected morphology to mechanism; condition monitoring and SHM turned snapshots into histories; prognosis and digital twins connected present evidence to possible futures.

No stage abolished the one before it. A model still needs an as-built geometry, a sensor still needs calibration, an anomaly still needs a mechanism, and a recommendation still needs a consequence model. The field advances when each layer states what it observed, how it could be wrong, and what independent evidence would discriminate among explanations.

Technical diagnostics therefore sits between measurement and decision. Its ethical and engineering duty is not to produce a confident label but to make the evidential path auditable: from structure or machine, through transduction and processing, to hypothesis, uncertainty, intervention, and learning. That is the durable scope articulated by the Handbook of Technical Diagnostics and extended by the century of practice that followed its constituent traditions [1].

Appendix A. Selected chronology

Table 3. Selective milestones in the development of technical diagnostics; dates mark documented developments, not universal adoption.

PERIOD	DEVELOPMENT	DIAGNOSTIC SIGNIFICANCE
1638	Galileo publishes Two New Sciences	Beam strength and fracture become subjects of mathematical mechanics.
late 1700s	Steam-engine indicator practice develops	Cylinder pressure is recorded against piston travel, making performance losses visible.
1800	Herschel identifies infrared radiation	Invisible thermal radiation enters experimental science.
1820s–1840s	Elasticity and strength theories mature	Stress, strain, and deflection become calculable diagnostic expectations.
1858–1870	Wöhler conducts railway-axle fatigue tests	Repeated-load failure is organized into stress–life evidence.
1860s	Engine indicators become portable commercial instruments	Comparative performance diagnosis spreads through steam engineering.
1875	Metre Convention is signed	International measurement traceability gains a durable institution.
1879	Hughes demonstrates material effects on induction coils	A foundation for practical eddy-current testing is established.
1890s	Oil-and-whiting crack detection used in railway shops	Surface-breaking defects are revealed by penetrant action.
1895	Röntgen discovers X-rays	Internal structure becomes observable through radiographic projection.
1911	ASME begins work on a uniform boiler code	Failure experience is converted into common construction and inspection rules.
1914–1915	First ASME Boiler Code edition appears	Pressure-equipment assurance becomes institutional and repeatable.
1920s	Magnetic-particle inspection enters industrial practice	Leakage fields make surface and near-surface cracks visible.
1921	Griffith publishes energy theory of fracture	Flaw size and fracture energy explain strength below theoretical cohesion.
1931	Coker and Filon publish Treatise on Photo-Elasticity	Whole-field stress patterns become a mature experimental method.
1931–1933	Ruska and Knoll build early electron microscopes; Ruska surpasses optical resolution	Microstructure and fracture morphology gain far higher resolution.
1938	Bonded resistance strain gauges are developed	Local strain becomes practical to instrument on real structures.
1940s	Liberty-ship fractures intensify materials investigations	Brittle transition, welding detail, and crack arrest reshape fracture practice.
1941	American Industrial Radium and X-Ray Society is founded	A predecessor of ASNT professionalizes industrial NDE.

PERIOD	DEVELOPMENT	DIAGNOSTIC SIGNIFICANCE
1942	Firestone pulse-echo flaw-detector patent is granted	Reflected ultrasound becomes an internal inspection method.
1943	NACE is founded	Pipeline corrosion knowledge becomes an organized profession.
1945	Miner publishes cumulative-fatigue rule	Variable-amplitude histories gain a simple engineering damage measure.
1950	Kaiser documents acoustic-emission behavior	Active damage can be monitored through transient elastic waves.
1951	Weibull publishes wide-applicability strength distribution	Population variability and weakest-link reasoning become practical.
1952	Larson–Miller parameter is published	Creep-rupture behavior is organized across time and temperature.
1953	Archard publishes sliding-wear relation	Tribological degradation gains a compact quantitative model.
1954–1955	Comet losses and inquiry drive full-scale fatigue investigation	Wreckage, pressure testing, and stress concentration reshape aircraft assurance.
1957	Irwin formalizes stress intensity	Crack-tip fields support quantitative fracture assessment.
1960	Kalman formulates state observability	Internal state inference becomes a formal systems question.
1963	Paris and Erdogan publish crack-growth law	Fatigue crack propagation can be related to stress-intensity range.
1965	Cooley and Tukey publish the FFT algorithm	Routine digital spectral analysis becomes computationally feasible.
1967	Silver Bridge collapses	Inaccessible critical details and nonredundancy transform bridge inspection policy.
1968–1971	U.S. national bridge inspection system is established	Periodic inventory and condition assessment become national infrastructure.
1970s	Commercial vibration analyzers and route programs expand	Machine condition is trended through repeatable spectra and phases.
1978	Photosensitivity in optical fiber is reported	The foundation for fiber Bragg grating sensing is established.
1980	MIL-STD-1629A codifies FMECA procedure	Failure modes, effects, and criticality are systematically enumerated.
1980s	Industrial computed tomography emerges	Radiographic projections become three-dimensional internal volumes.
1987	Reiter publishes a theory of model-based diagnosis	Conflicts between expected and observed behavior support systematic hypotheses.
1989	Aloha Airlines Flight 243 report	Aging-aircraft inspection confronts multiple-site fatigue and corrosion.
1990s	Digital radiography and phased-array ultrasonics spread	Encoded imaging, storage, and steerable beams broaden NDE evidence.
2000	Hatfield derailment	Rolling-contact fatigue and maintenance-information failures become inseparable lessons.
2003	ISO 13374-1 organizes condition-monitoring data processing	Acquisition, manipulation, detection, assessment, and advice gain a shared architecture.

PERIOD	DEVELOPMENT	DIAGNOSTIC SIGNIFICANCE
2004	ISO 13381-1 formalizes prognostics guidance	Remaining-life processes gain common concepts and requirements.
2006–2007	Wireless and statistical SHM syntheses appear	Distributed sensing and pattern recognition frame asset-scale diagnosis.
2007	I-35W bridge collapses	Design capacity, load history, and inspection scope are shown to be distinct evidence problems.
2008	NASA PHM challenge uses C-MAPSS data	Reusable run-to-failure benchmarks accelerate data-driven prognosis.
2009	MIL-HDBK-1823A updates POD guidance	Inspection reliability is expressed with target-size curves and confidence.
2012	NASA presents the digital-twin paradigm	As-built identity, live data, physics, and uncertainty are joined in one model concept.
2013	Handbook of Technical Diagnostics is published	The field is synthesized across methods, machinery, structures, systems, and heritage.
2021	ISO 23247 digital-twin framework is published	Manufacturing twins gain shared concepts, architecture, attributes, and exchange requirements.
2024	NIST publishes metal-AM monitoring and NDE roadmap	Process signatures, material state, and qualification are treated as one measurement chain.

Appendix B. Glossary

Working definitions used in this article. Terms are alphabetized; standards and sectors may use narrower definitions.

Acceptance criterion. A rule or limit used to decide whether a measured or characterized condition is acceptable for a stated purpose.

Acoustic emission (AE). Transient elastic waves generated by active processes such as crack growth, friction, leakage, or fiber breakage.

Alarm. A configured notification that a monitored variable or feature crossed a rule; it is not, by itself, a diagnosis.

Anomaly. A departure from an expected baseline, distribution, model, or peer population.

Asset genealogy. The identity, material, manufacture, installation, repair, configuration, and service history of a physical item.

Baseline. A qualified reference condition against which later observations are compared.

Calibration. Operations that establish the relation between indicated values and reference values under specified conditions.

Causal isolation. Testing or analysis that discriminates among competing mechanisms capable of producing similar symptoms.

Computed radiography (CR). Digital radiography using a reusable imaging plate that is scanned after exposure.

Computed tomography (CT). Reconstruction of cross-sectional or volumetric attenuation information from multiple projections.

Condition monitoring. Acquisition and interpretation of information that describes the condition of an item over time.

Confidence bound. A statistical bound expressing uncertainty in an estimated quantity or performance curve.

Consequence assessment. Evaluation of what an identified condition could do to function, safety, environment, cost, or mission.

Coverage. The portion of a target volume, surface, state space, or failure-mode set that an observation system can examine.

Crack-growth law. A relation used to estimate crack extension under a specified loading and environmental history.

Damage tolerance. An assurance approach that assumes flaws may exist and controls risk through analysis, inspectability, and timely detection.

Data fusion. Combination of signals, features, models, or decisions from multiple evidence sources.

Defect. A discontinuity or condition that fails a stated acceptance requirement; not every discontinuity is a defect.

Degradation mechanism. A physical or chemical process by which condition changes, such as fatigue, corrosion, creep, or wear.

Diagnostic coverage. The fraction or set of relevant faults or damage states that a diagnostic system can detect or isolate under stated conditions.

DICONDE. Digital Imaging and Communication in Nondestructive Evaluation, a standard practice for interoperable images and metadata.

Digital image correlation (DIC). Optical estimation of displacement and strain fields by tracking image texture.

Digital thread. Linked lifecycle information that preserves identity and relationships across design, manufacture, operation, inspection, and maintenance.

Digital twin. A maintained digital representation of an identified physical counterpart, updated with data for a defined use such as diagnosis or prediction.

Discontinuity. An interruption or variation in physical structure or material; its acceptability requires separate evaluation.

Domain shift. A change between development and use conditions that alters the statistical or physical relation between data and state.

Eddy-current testing (ET). Electromagnetic inspection based on changes in induced current flow and probe impedance.

Effectivity. The exact serial-number, build, modification, or configuration population to which information applies.

Environmental normalization. Adjustment or modeling used to separate temperature, humidity, load, or other environmental effects from damage-sensitive change.

False call. A reported relevant condition when the target condition is absent or not supported.

Fault. An abnormal physical state or causal condition capable of impairing required function.

Fault tree. A deductive model that decomposes an undesired event into logical combinations of contributing events.

Feature. A quantity extracted from raw observations for comparison, classification, estimation, or diagnosis.

Fitness for service. Engineering assessment of whether equipment containing a flaw or degradation can continue operating under defined conditions.

Fractography. Examination and interpretation of fracture surfaces to identify origin, propagation, loading, and mechanism.

Full-matrix capture (FMC). Ultrasonic acquisition in which each array element transmits and all elements receive for later reconstruction.

Health indicator. A scalar or vector intended to track progression from a reference condition toward functional failure.

Indication. An instrument or examination response that may require interpretation; it is not automatically a flaw.

Infrared thermography. Imaging and analysis of infrared radiation to infer surface temperature or heat-flow behavior.

Inspection interval. Time, usage, or cycles between examinations, ideally set from degradation rate, consequence, and detection reliability.

Intervention test. A controlled change in load, configuration, boundary condition, or component used to discriminate causal hypotheses.

Leakage field. Magnetic flux emerging from a ferromagnetic surface because a discontinuity perturbs the magnetic path.

Lift-off. Separation between an electromagnetic probe and the test surface, often a major confounding variable.

Load path. The route by which applied forces and moments are transmitted through a structure or assembly.

Localization. Estimation of the spatial position or source region of an indication or anomaly.

Maintenance-induced fault. Damage, misassembly, contamination, or configuration error introduced during maintenance.

Modal assurance criterion (MAC). A measure of similarity between two mode-shape vectors.

Modal testing. Experimental identification of natural frequencies, mode shapes, and damping from measured dynamic response.

Model residual. Difference between an observed quantity and the value predicted by a model under stated inputs and assumptions.

NDE / NDT. Nondestructive evaluation or testing: examination of materials or components without impairing their intended future use.

Noise floor. Background response below which relevant signals cannot be reliably distinguished.

Operating regime. A bounded state such as speed, load, temperature, process recipe, or control mode that conditions expected behavior.

Order tracking. Analysis of vibration or sound relative to rotational speed so features remain aligned with shaft orders during speed change.

Out-of-plane motion. Motion normal to an image plane that can bias apparent in-plane displacement in optical measurements.

Phased-array ultrasonics (PAUT). Ultrasonic testing using controlled timing across array elements to steer or focus beams.

Physics of failure. Use of material, load, environment, and mechanism models to explain or predict degradation.

Probability of detection (POD). The probability that a defined inspection system reports a target as a function of target size or other parameter.

Process signature. Measured behavior of a manufacturing or operating process that may correlate with resulting condition.

Prognosis. Prediction of future condition, failure probability, or remaining useful life under stated assumptions.

Proof test. Application of a specified load or pressure to demonstrate minimum capacity or expose certain weaknesses.

Qualification. Demonstration that a procedure, equipment, personnel, and conditions can meet stated performance requirements.

Radiographic testing (RT). Inspection using penetrating ionizing radiation and a detector to form attenuation images.

Reference block. A specimen with controlled material, geometry, and reflectors or discontinuities used to set or check inspection response.

Remaining useful life (RUL). Estimated time or usage until a defined functional or safety threshold is reached.

Repeatability. Agreement of results under the same method, operator, equipment, location, and short time interval.

Reproducibility. Agreement of results when relevant conditions such as operator, equipment, laboratory, or time change.

Residual stress. Stress retained in a body without external load, often created by welding, forming, heat treatment, or assembly.

Risk-based inspection (RBI). Planning that prioritizes inspection using estimated likelihood and consequence of failure.

Sensitivity. Change in instrument response per change in the quantity or target characteristic of interest.

Sensor drift. Gradual change in sensor output unrelated to the measurand.

Sizing. Estimation of discontinuity dimensions, distinct from detection and localization.

Spall. Material detached from a surface, often through contact fatigue, corrosion, impact, or thermal damage.

Spectral sideband. Frequency component offset from a carrier or order, often produced by modulation from a fault or process.

State estimation. Inference of internal system variables from measurements and a dynamical model.

Strain gauge. A transducer whose electrical or optical response changes with deformation.

Stress concentration. Localized amplification of stress caused by geometry, discontinuity, contact, or material change.

Structural integrity. Ability of a structure or component to perform its required load-bearing function with acceptable risk.

Structural-health monitoring (SHM). Persistent or repeated sensing and inference used to detect, locate, characterize, or assess structural change.

Technical diagnostics. Evidence-based identification and explanation of faults, degradation, or integrity states in physical structures and systems.

Thermal excitation. Controlled heating or cooling used to make subsurface differences visible through transient heat flow.

Threshold. A decision boundary applied to a measurement, feature, probability, or risk estimate.

Time-of-flight. Travel time used to estimate acoustic, ultrasonic, radiographic, or optical path distance.

Traceability. Documented chain linking a measurement result to references, transformations, identity, and responsible operations.

Trend. Ordered series of comparable observations used to estimate change over time or usage.

Tribology. Science and engineering of friction, lubrication, wear, and interacting surfaces in relative motion.

Ultrasonic testing (UT). Inspection using high-frequency mechanical waves and their transmission or reflection.

Uncertainty. Quantified or stated doubt about a measurement, model, inference, or future condition.

Validation. Evidence that a method or model is adequate for its intended real-world use.

Vibration envelope. Demodulated amplitude history or spectrum used to reveal repetitive impacts and bearing-related modulation.

Voxel. A volumetric picture element in a reconstructed three-dimensional data set.

Wear debris. Particles generated by interacting surfaces and carried in lubricant, filters, or deposits.

Witness mark. Physical mark that records relative motion, contact, alignment, or prior position.

Appendix C. Evidence taxonomy

Table 4. Evidence families, their strongest questions, recurring blind spots, and minimum identity or trust requirements.

Evidence	Strongest questions	Characteristic blind spots	Identity / trust requirements
Sensory and visual	Surface condition, leakage, motion, sound, odor	Broad coverage; immediate context	Access, lighting, subjectivity, hidden damage
Dimensional and geometric	Clearance, alignment, profile, deformation, settlement	Direct comparison with geometry or tolerance	Datum choice, temperature, setup and uncertainty
Operating and process	Pressure, flow, power, speed, load, control state	Connects condition to function and exposure	Confounding regimes, sensor drift, missing context
Strain and displacement	Local or full-field structural response	Tests load paths and models	Bonding, thermal effects, spatial coverage
Vibration and modal	Waveforms, spectra, orders, modes, damping	Sensitive to dynamic and rotating faults	Environment, operating state, non-uniqueness
Ultrasonic and acoustic	Echoes, transmission, emissions, source locations	Internal or active-damage sensitivity	Orientation, coupling, propagation and noise
Electromagnetic	Impedance, leakage flux, field response	Fast near-surface or volumetric screening	Material properties, lift-off, geometry
Thermal	Temperature fields and heat-flow transients	Noncontact whole-field surveys	Emissivity, reflection, excitation and environment
Radiographic and tomographic	Projection images and reconstructed volumes	Internal geometry with durable images	Energy, superposition, artifacts, detectability
Material and microstructural	Hardness, chemistry, phases, surfaces, fracture morphology	Mechanism-level discrimination	Sampling, preparation, representativeness
History and provenance	Loads, cycles, repairs, genealogy, prior indications	Explains exposure and sequence	Incomplete records, terminology and survivor bias
Model and probabilistic	Residuals, state estimates, risk, POD, RUL	Integrates evidence and supports decisions	Assumption error, calibration, domain shift
Intervention and retest	Response to controlled load, isolation, repair, or substitution	Strong causal discrimination	May alter or destroy evidence; operational risk

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