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Research and Innovation in Mainframe Application Modernization

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ABSTRACT

Legacy mainframe application modernization is a watershed moment where mature enterprise computing models meet modern technological breakthroughs based on artificial intelligence prowess, cloud-native design, and distributed system design methodologies. Organizations globally must address the need to transform missioncritical workloads executing billions of daily transactions in banking, insurance, government, and telecommunications industries while maintaining institutional knowledge imparted by decades of incremental coding. Today's transformation efforts aim beyond sheer cost reduction goals to achieve holistic business value realization by achieving enhanced agility, improved scalability, and seamless extensibility into evolving digital environments. Code analysis automation based on neural language models trained on large corpora of programming code allows for systematized legacy codebase comprehension, dependency mapping, and business rule extraction from unwritten procedural implementations. Microservices design styles enable the breaking down of large monolithic programs into independently deployable service components, which are conducive to parallel software development flows, fine-grained scaling, and fault isolation mechanisms that enhance device resilience. Client-led innovation through piloting, open-source engagements, and partner-led industry initiatives builds empirical proof supporting transformation strategies and developing repeatable methodologies suitable for deployment within diverse organizational settings. Persistent issues, including technical debt buildup, organizational change management, distributed data consistency, and security framework evolution, mandate interdisciplinary solutions based on technical breakthroughs combined with cultural evolution. Newer computational models, such as edge computing, federated learning, and intelligent orchestration frameworks, suggest continued evolution of enterprise systems into autonomous, self-healing systems achieving unparalleled operational effectiveness while meeting extant regulation requirements, data privacy mandates, and sustainability obligations defining enterprise computing futures.

Keywords: Mainframe Modernization, Microservices Architecture, Legacy System Transformation, Cloud-Native Computing, Technical Debt Management, Artificial Intelligence

1. Introduction

Mainframe application modernization is an important confluence of time-tested enterprise computing methodologies and modern technological innovation. Defying prognoses of obsolescence, mainframes persist in processing some 87% of all credit-card transactions worldwide and executing more than 30 billion business transactions daily in banking, insurance, and governments [1]. Businesses seeking mission-critical workload transformation more and more acknowledge that innovation is more than about reducing costs in order to realize huge business value, with modernization projects exhibiting transaction throughput processing and resource efficiency improvement of between 40% and 60% [2].

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Today's companies collaborate with academic centers, technological vendors, and consultancies of experts to extend modernization capabilities. Complexity of systems—with financials maintaining COBOL code bases of over 300 million lines and insurance providers executing applications from over 40-year-old development ages—needs sophisticated techniques, including automated code analysis, transform engines with AI-driven functions, and risk-minimizing migration products [1].

Modern research studies code translation facilitated by artificial intelligence that attains more than 92% accuracy levels in preserving business logic, hybrid cloud designs that ensure workload portability, microservices break-up strategies, mainframes implemented in a containerized manner, and customer inputs that define the next-gen enterprise infrastructure [2]. The combination of automated migration toolsets, machine learning-driven dependency mapping, and continuous integration architecture is a shift from legacy lift-and-shift methodologies to smart, dynamic modernization strategies.

2. Historical Background and State of Research

Mainframes reigned in enterprise computing for some decades, with systems from the 1960s and 1970s still running mission-critical applications, but the rigidity of architecture created genuine issues when online demands grew. It was early efforts that centered on migration processes of code, business logic isolation, and reducing downtime, with early research creating ground-up designs with a predisposition to systematization of legacy codebases [4].

The early 1990s and early 2000s industry studies indicated strong backward compatibility and riskreduced transition directions, creating detailed papers on tool-centered migration and reverse engineering techniques based on several abstraction mechanisms such as control flow graphs, data flow graphs, and architectural recovery methods [4]. These papers laid out early taxonomy models for the reverse engineering methodology classification based on abstraction level, degree of automation, direction, and scope limits [4].

Newer methods, in turn, have shifted in the direction of holistic approaches that consider technical, organizational, and human factors dimensions. The integration of gamification concepts is a significant methodological advancement, with empirical studies concluding that systems of rewards based on achievement increase the degree of uptake among developers of modernization tools by adoption rates of over 85% compared with earlier training methods that achieve lasting adoption of below 40% [3]. University and commercial labs today analyze legacy code analysis automation with higher-order static analysis, dynamic profiling, and machine learning pattern recognition while uncovering organizational change mechanisms such as gamified learning paths and reward systems that propel development groups in longer-duration transformation efforts [3][4].

Era	Research Focus	Key Methodologies	Innovation Drivers
1990s-Early 2000s	Code migration procedures, business logic isolation, and backward compatibility	Tool-driven migrations, system emulation, reverse engineering with control flow graphs and data flow diagrams	Risk minimization, downtime reduction, functionality preservation
Mid-2000s-2010s	Architectural recovery, abstraction mechanisms, and taxonomic	Classification across abstraction levels, automation degrees, directionality, and scope	Systematic transformation approaches, design artifact reconstruction

	frameworks	boundaries	
2010s-Present	Holistic strategies addressing technical, organizational, and human factors	Gamification principles, achievement-based systems, and machine learning-based pattern recognition	Developer engagement enhancement, sustained practice adoption, community-driven innovation
Contemporary	Cloud-native design, hybrid orchestration, automated legacy code analysis	Advanced static analysis, dynamic profiling, gamified learning pathways, and incentive structures	Organizational change management, cultural transformation, and extended transformation initiatives

Table 1. Evolution of Mainframe Modernization Research Approaches [3, 4].

3. Key Innovation Themes in Mainframe Modernization

Automation becomes the overriding theme by exploiting advanced code analysis software, automated tests, and accelerated refactoring efforts. Code conversion being conducted by automation with the help of artificial intelligence allows accelerating refactoring automation frameworks with much fewer manual interventions, with empirical validation verifying that refactoring interventions conducted in a planned fashion achieve measurable benefits in terms of maintainability, reusability, and comprehensibility [5]. Selected applications of the extract method refactoring, rename variable efforts, and move method transformations cumulatively assist software quality metrics, with results of research verifying improved modularity, decreased cyclomatic complexity, and improved coupling metrics, justifying further modernization efforts [5].

Interoperability is another key theme, with application programming interface advancements enabling mainframes to communicate with contemporary technology stacks through containerization. The microservices journey is an important architectural transition from monolithic to distributed, independently deployable service compositions, although retransformation poses significant obstacles in technical, organizational, and operating scopes [6]. Important challenge buckets are architectural complexity due to distributed coordination needs, deployment overhead, managing independently versioned services, organizational redesign driven by Conway's Law tenets, and technology hurdles, including service discovery, distributed transactions, and data consistency schemes [6].

Empirical studies find microservices architecture brings with it latency concerns whereby singlemonolith function calls turn into network-bound inter-servicecallsls potentially adding milliseconds to transaction duration, deployment complexity necessitating advanced orchestration platforms, and observability issues necessitating full observability frameworks that capture request flows through distributed service meshes [6]. Gateway architecture with protocol translation and API aggregation supporting communication between mainframe refactoring components and modern microservices, supporting hybrid deployment models while tackling issues such as distributed data management, service version strategies, and resilience patterns utilizing circuit breakers and timeouts [5][6].

4. Fuelling Change through Emerging Technology

Artificial intelligence, machine learning, and big data analytics remake modernization substantially by deploying probabilistic and deep learning techniques grounded in the naturalness hypothesis, i.e.,

software is statistically similar to natural language. Intelligence-based code comprehension tools utilizing neural language models, including recurrent neural networks with long short-term memory units, transformer architecture with mult-head self-attention mechanisms, and graph neural networks that operate on abstract syntax trees, automatically categorize legacy code structures, recommend optimal migration paths, and fine-tune the migrated code [7].

Machine learning models trained on large code bases with hundreds of millions of lines take probabilistic modeling strategies, including n-gram language models, neural probabilistic models that learn distributed representations, and structured prediction models that learn anomalous mainframe activities for predictive maintenance and security analysis applications [7]. Code completion models trained on large repositories achieve superb performance with accuracy far beyond manual predictions by developers, method name completion that is consistent with human expert corrections, and defect prediction that identifies bug-prone modules with accuracy far beyond traditional static code analysis tools [7].

Cloud platforms redefine modernization through serverless computing paradigms, representing a natural evolution where developers focus exclusively on business logic while cloud providers manage infrastructure concerns. Serverless computing eliminates server management by automatically provisioning ephemeral compute resources responding to event triggers, scaling from zero to thousands of concurrent executions within seconds, and billing based on actual consumption measured in 100-millisecond increments [8]. These platforms excel for event-driven workloads with sporadic invocation patterns and embarrassingly parallel computations, while presenting challenges for workloads requiring sustained execution, stateful processing, or predictable sub-millisecond latency guarantees [8]. Machine learning-driven code analysis combined with serverless platforms enables data-driven modernization decisions, rapid experimentation, and composition of complex business processes through event-driven orchestration patterns [7][8].

5. Client-focused Research Contributions

Organizations fuel innovation with pilot projects, in-house labs, and open-source initiatives studying system modernization strategies in a systematic manner. Financial organizations design proprietary code migration automation frameworks that further increase migration precision and decrease system outage, with survey research involving 72 software development experts finding that microservices adopting organizations experience improved deployment frequency with 45.8% deploying multiple times daily, improved scalability with 63.9% experiencing better scaling ability, and greater team autonomy [9].

Experimentation of the event-driven architecture by software industry clients involves adopting asynchronous communication schemes, with an estimate of 69.4% of the organizations utilizing RESTful HTTP APIs as main inter-service communication mechanisms and 44.4% utilizing message queues, thus supporting real-time propagation of data with millisecond latencies [9]. Client-oriented projects create pioneer documentation, such as published methods and architectural decision records, with the respondents implementing applications of domain-driven design principles in 55.6% of the applications, as well as in alignment with business capability in 50% of the implementations [9].

Through implementation case studies, organizations advance theoretical concepts toward tangible outcomes, with comprehensive surveys synthesizing insights from extensive literature reviews analyzing 139 primary studies examining microservices adoption patterns, architectural principles, and migration challenges [10]. Successful migrations employ systematic decomposition methodologies including strangler fig patterns, decomposition by business capability, and anticorruption layer patterns [10]. Survey evidence indicates organizations encounter challenges, including distributed data management identified by 47.6% of studies, service granularity determination highlighted by 31.4%,

and organizational restructuring noted by 23.8% requiring cultural transformation alongside technical migration [10]. Empirical contributions reveal adoption motivations, including improved scalability cited by 64.7% of studies, enhanced maintainability referenced in 58.8%, and accelerated development velocity mentioned in 52.9%, while documenting challenges, including increased monitoring complexity reported in 42.9%, testing difficulties noted in
38.1%, and network latency concerns affecting 33.3% [9][10].

Aspect	Observation Category	Key Findings	Industry Sector Applications
Deployment Frequency	Operational Improvements	Transition from quarterly/monthly to multiple daily deployments, enhanced team autonomy	Financial institutions, e-commerce platforms
Scalability Enhancement	Technical Performance	Better scaling capabilities through independent service scaling, improved resource allocation	Cloud service providers, SaaS platforms
Communication Patterns	Inter-service Integration	RESTful HTTP APIs as the primary mechanism, and message queues for asynchronous processing	Manufacturing, realtime analytics systems
Decomposition Strategies	Architectural Approaches	Domain-driven design principles, business capability alignment, and strangler fig patterns	Enterprise software, healthcare IT
Migration Challenges	Implementation Obstacles	Distributed data management, service granularity determination, and organizational restructuring	Cross-sector transformation initiatives
Adoption Motivations	Strategic Drivers	Improved scalability, enhanced maintainability, and accelerated development velocity	Technology companies, digital transformations

Table 2. Microservices Adoption Patterns and Organizational Outcomes [9, 10].

6. New Procedures and Techniques

State-of-the-art modernization efforts make increased use of machine learning-driven code analysis for discovering dependencies and visualizing business rules, with an advanced graph neural net architecture for representing source code as structured relational data that preserves syntactic and semantic relations. Companies integrate machine learning with human-in-the-loop systems, deploying global relational models that encode programs as graphs with code entities as nodes, while edges hold relations such as function calls and data dependencies [11]. Graph neural models with message passing mechanisms that outperform sequential models on variable misuse detection, method name prediction, and program repair demonstrate empirical results that achieve global relational models with cross-file dependencies, achieving an accuracy gain of more than 15 percentage points compared with local models [11].

Agile migration strategies and continuous integration techniques assist in rapid adaptation to shifting requirements. Microservices architecture is a transformative technique that requires understanding contextual issues, including organizational design whereby team independence impacts service

boundaries, technological concerns that specify deployment models, and business requirements that specify architectural trade-offs [12]. Major architectural designs include implementations of the API gateway, service registry that ensures dynamic service resolution, and circuit breaker pattern that prevents cascading failures [12]. Successful implementations manage data by utilizing patterns including database per service, event sourcing, and the saga pattern that handles distributed transactions [12].

Global relational models of program structure discern optimal service boundaries by finding in the graph communities that denote cohesive sets of functionality with few inter-community edges, such that automated decomposition suggestions balancing service granularity trade-offs can be made [11][12]. Integration necessitates resolving contextual constraints such as containerization technologies, orchestration platforms that automate scaling, and service mesh architectures that offer observability, security, and traffic management [12]. Graph neural models of API usage patterns make consistent interface design suggestions, detect breaking changes, and indicate backwardly compatible evolution strategies such that modernization is turned into systematic, analytically guided processes that integrate machine learning insights with architectural pattern design [11][12].

7. Impact Assessment: Performance and Scalability

Studies show that mainframe workload modernization ensures significant scalability and performance enhancements through architectural redesigns that take advantage of distributed computing models. Systematic mapping reviews of 84 main papers indicate that microservices migration tackles key aspects such as strategies for decomposition, whereby 29% of the studies concern finding the best service boundaries, migration strategies whereby 25% examine systematized methodologies for transformation, and granularity issues whereby 19% directly answer service sizing [13].

Properly granularized microservices enable independent scaling, reduce failure blast radius, and accelerate development velocity, though distributed complexity introduces latency from network communications and eventual consistency requirements complicating data management [13]. Studies examining granularity trade-offs demonstrate service size significantly impacts performance, with fine-grained services under 100 lines experiencing degradation from excessive inter-service communication while services exceeding 10,000 lines demonstrate monolithic characteristics [13].

REAL-WORLDTMigration experience reports chronicling systematic change realizing measurable gains, including increased deployment frequency shifting from quarterly to daily deployments, infrastructure cost savings of 30%-50% with elastic scaling, and enhanced fault tolerance with failures contained [14]. Migration strategies stress incremental change starting with vertical decomposition, releasing API gateway designs, creating deployment environments with containers, and steadily strangling legacy behavior [14]. Performance monitoring shows upfront extractions can suffer shortterm performance due to network latency, but iterations of optimization deploying caching strategies ultimately meet or exceed original performance baselines, especially with high-concurrency loads [14]. Experience reports chronicle detailed results, including improved time for APIs to respond from 800 milliseconds down to 200-300 milliseconds, increased transaction throughput from 50 to more than 200 transactions per second, and improved infrastructure utilization reaching 60-70% CPU usage compared to 20-30% typical of monolithic applications [13][14].

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Performance Dimension	Legacy System Characteristics	Modernized System Characteristics	Implementation Considerations
API Response Time	Average latencies in hundreds of milliseconds, sequential processing	Reduced latencies through parallel service invocations, optimized caching	Requires network optimization, reduced contention
Transaction Throughput	Limited concurrent processing, vertical scaling constraints	Increased capacity through horizontal scaling across containerized instances	Orchestration platform deployment, load balancing
Infrastructure Utilization	Low CPU utilization on dedicated servers, over-provisioned capacity	Higher utilization through bin-packing multiple services, efficient resource sharing	Container orchestration, dynamic resource allocation
Deployment Frequency	Quarterly releases requiring extensive coordination	Daily or multiple daily deployments through automated pipelines	CI/CD implementation, independent service deployment
Infrastructure Costs	Fixed capacity provisioning, capital expenditure model	Cost reduction through elastic scaling, consumption-based pricing	Cloud migration, auto-scaling policies
Fault Tolerance	Cascading failures across monolithic components	Isolated failures, graceful degradation through circuit breakers	Resilience patterns, service mesh implementation

Table 3. Performance and Scalability Improvements in Microservices Migration [13, 14].

8. Collaboration Models and Ecosystem Partnerships

Cooperation is central to breakthrough innovation, as systemic evidence identifies open-source collaborative development models as reducing technological development time and knowledge spread substantially. Industry-campus collaboration allows for shared development, with deep surveys discovering open-source development encompassing heterogeneous project types utilizing heterogeneous coordination mechanisms, including centralized control, distributed peer review, and hybrid models of governance [15]. Technology vendors and system integrators forge communities of best practice with open-source repositories, lowering entry barriers, enabling asynchronous collaboration, and spreading knowledge with transparent development processes [15].

The critical success factors encompass modular architecture supporting parallel development, detailed documentation lowering entry barriers, and attentive maintainer interaction yielding prompt feedback [15]. Community interventions with empirical studies disclosing basic transformations in contributor motivations with time, in which longitudinal studies show early developers contributing chiefly to build skills and build reputation, with senior developers more valuing intrinsic motivations such as mental stimulation and altruistic intentions [16].

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Quantitative study of motivation pattern through 242 questionnaire responses identifies that career stage is highly significant in drivers with students prioritizing skill development by 4.2 and resume building by 3.8 on five-point scales, while accomplished developers prioritizing ideological beliefs by

4.5, community belonging by 3.9, and giving back by 4.3 [16]. Incentives for initial contribution are often pragmatic needs, with 68% specifying scratching personal itches as the first motivation for contribution, while long-term contribution demands cultivation of social relationships, sense of possession, and recognition by peers [16]. Identification of maturing motivations allows crafting of an engagement strategy that enlists new entrants through issues suitable for beginners, maintains accomplished developers through technical issues, and cultivates communities that include everyone [15][16].

9. Innovation and Research Issues

In spite of advancements, significant issues remain with complexity and documentation gaps in legacy codebases that were grown by incremental change over decades. Extensive empirical studies of 1,820 practitioners describe technical debt management practice as heterogeneous, with only 37% of reports stating that organizations have explicit technical debt catalogs, 41% stating informal tracking, and 22% stating no deliberate management [17]. Practitioners cite key barriers being difficulty in making debt transparent to stakeholders, with 68% reporting difficulty in explaining implications to management, complexity in prioritization, with 54% reporting difficulty in knowing items that need attention, and too little time being allocated, with 73% stating calendars hardly ever contain explicit time allocations for paying down technical debt [17].

Accumulated debt creates vicious cycles where poor quality slows feature development, necessitating schedule pressure, incentivizing further quality shortcuts, with high-debt codebases requiring 50100% additional effort for equivalent changes, experiencing defect rates 2-4 times higher, and suffering knowledge erosion where complex undocumented code becomes incomprehensible [17]. Organizational inertia and risk aversion decelerate innovation, with systematic reviews analyzing 16 primary studies revealing migration challenges span technical obstacles, including distributed data management and inter-service communication latency, organizational impediments, including team restructuring and skill development, and operational complexities, including monitoring distributed systems and managing deployment pipelines [18]. Effective transformations make use of systematic decomposition methods, strangler fig approaches, and whole-systems testing frameworks [18]. An average migration time of 6 months for small applications to more than 3 years for large systems is reported by organizations, with team sizes from 3-5 developers to 20-50 staff, and investment spend from hundreds of thousands to millions of dollars [18]. Chief among the critical success factors were executive sponsorship, incremental delivery methodologies, and organizational learning investments, while among common pitfalls were premature optimization, inadequate monitoring infrastructure, and inadequate automation [17][18].

Challenge Category	Specific Obstacles	Organizational Impact	Mitigation Strategies
Technical Debt Visibility	Difficulty communicating debt implications to nontechnical stakeholders	Insufficient resource allocation, deferred quality improvements	Explicit debt inventories, businessterm communication frameworks

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Debt Prioritization	Struggle determining which debt items warrant immediate attention versus deferral	Suboptimal remediation sequencing, continued quality erosion	Risk-based prioritization, impact assessment models
Time Allocation	Project schedules rarely include explicit allocations for debt repayment	Accumulated debt creates vicious cycles, feature development slowdown	Dedicated refactoring sprints, continuous improvement practices
Distributed Data Management	Transition from ACID transactions to eventual consistency models	Data consistency challenges, transaction coordination complexity	Saga patterns, distributed transaction coordinators, and event sourcing
Service Granularity	Determining optimal service boundaries, balancing autonomy and complexity	Either excessive operational overhead or limited scalability benefits	Domain-driven design, bounded context identification, and iterative refinement
Organizational Restructuring	Team structure alignment with service boundaries, cultural transformation	Conway's Law implications, skill gap challenges, and resistance to change	Cross-functional teams, DevOps adoption, training programs

Table 4. Technical Debt Management and Migration Challenge Categories [17, 18].

10. Future Directions and Frontiers for Research

The future ever more looks to multidisciplinary solutions combining artificial intelligence, cybersecurity, cloud engineering, and business transformation. New research considers smart transportation systems in which edge computing nodes located at roadside infrastructure process sensor data from vehicles locally with millisecond-scale response times supporting safety-critical applications such as collision avoidance and autonomous vehicles with sub-100 millisecond latency guarantees [19]. Edge computing offers new platforms in hierarchical architecture extending from cloud data centers through edge servers at the network gateways to embedded edge devices, all supporting tiered processing whereby time-critical computations run at the edge with resourcehungry analytics supporting cloud infrastructure [19]. Key technical issues are resource limitations with edge devices that have reduced computational power and need optimal algorithm implementations, heterogeneity of networks with heterogeneous communication technologies that have different latency and bandwidth properties and need protocol adaptation, and increased vulnerabilities for security with distributed edge nodes that create increased attack surfaces [19]. Companies co-create next-gen instruments such as self-healing mechanisms and cognitive orchestration models. Focus more on digital trust, data privacy by edge processing that processes sensitive data on the local side without raw data transfer, and hyper-automation that marries intelligent edge nodes with cloud-based orchestration [20]. Studies explore social sensing applications such as disaster relief, in which edge computing allows for fast information consolidation in spite of network infrastructure destruction, public health applications processing body functions with privacy maintenance, and intelligent city applications integrating traffic control and emergency systems [20]. Main technical challenges involve task offloading optimization, strategies for resource allocation, and data management methods such as caching, synchronizing the distributed repositories, and applying lifecycle policies [20]. New frontiers investigate machine learning placement at edge devices, federated learning training models in a joint manner with no data centralization, and

edge-cloud collaboration systems, building grounds for distributed computing schemes of the next generation [19][20].

Conclusion

Mainframe software modernization has matured from brief-term tactical infrastructure upgrades to lengthy-term strategic enterprise transformation initiatives, basically redefining corporate computing capabilities through disciplined use of artificial intelligence, microservices architectures, and cloudnative deployment models. Integrative proof distilled from instructional literature, industry case experiences, and empirical practitioner questionnaires illustrates that successful differences necessitate holistic strategies addressing technical, organizational, and operating issues in concert in place of applying technological solutions in isolation. Graph neural networks inspecting program structure allow for computerized service boundary discovery, while refactoring strategies comprehensively improve code quality metrics supporting subsequent architectural evolution. Microservices decomposition schemes balance against granularity trade-offs, permitting independent service scaling and autonomous development teams, although distributed system complexity raises impediments across data consistency, transactional coordination, and operating observation, necessitating advanced tooling and mature organizational capabilities. Open-source community development models accelerate innovation through community-driven tool development, knowledge sharing, and collaborative problem-solving beyond organizational boundaries. Technical debt management strategies, risk mitigation strategies for migration, and incremental transformative approaches make it practical for organizations to modernize mission-critical mainframes while preserving operating continuity and value delivery throughout long-term transformation programs. Future directions include edge computing architectures for supporting applications with low-latency requirements, federated learning for maintaining data privacy, and autonomous orchestration frameworks for optimizing resource allocation based on learned behavioral dynamics. CA's combination of maturing technologies with established architectural designs, systematic concern with sociotechnical factors that affect adoption success, and continued investment in evidence-based decision-making combine to situate mainframe modernization as a maturing discipline permitting enterprises to safeguard valuable legacy investments while achieving modern architectural advantages, including scalability, resilience, and global scope supporting evolving requirements of the business.

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