

Automation and Management in Operating Systems: The Role of Artificial Intelligence and Machine Learning

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Abstract

The ever-increasing complexity of operating systems (OSes) poses challenges for traditional management approaches. This paper explores the potential of artificial intelligence (AI) and machine learning (ML) to revolutionize OS management, transforming it from a reactive task to a proactive dance of intelligent adaptation. We propose a block diagram outlining the stages of AI and ML integration, encompassing data input, system state analysis, decision making, optimization actions, and continuous monitoring. We then delve into specific applications of AI and ML in resource management, security and threat detection, performance optimization, self-healing mechanisms, and predictive maintenance. Implementation considerations, challenges, and evaluation methods are discussed, highlighting the need for data infrastructure, algorithm selection, explainability, fairness, security, and responsible development. We conclude by emphasizing the future directions of deeper integration, specialization, explainable AI, and collaborative intelligence, paving the way for OSes that are not just tools, but intelligent partners, anticipating our needs, adapting to our workflows, and creating a truly liberating user experience.

Keywords¹

Operating System Management, Artificial Intelligence, Machine Learning, Resource Management, Security, Performance Optimization, Predictive Maintenance, Explainable AI, Fairness, Collaborative Intelligence

1. Introduction

The world of operating systems (OS) has witnessed a fascinating metamorphosis. Once simple tools for managing hardware and software, they have become intricate ecosystems, juggling an ever-growing chorus of tasks and demands. This surge in complexity, while empowering users with unprecedented functionality, has also introduced formidable challenges [1]. Traditional management approaches, often reliant on manual configuration and static scripts, struggle to keep pace with the dynamic needs of these modern behemoths. Enter artificial intelligence (AI) and machine learning (ML), two revolutionary forces poised to reshape the landscape of OS management [2-6]. These technologies offer a glimmer of hope, promising to automate tedious tasks, anticipate problems before they arise, and optimize performance like never before [7-10].

In this article, we delve into the possibilities and advantages of integrating AI and ML into the core of OS management.

Imagine an OS that intuits your needs, allocating resources with pinpoint precision, predicting glitches before they flicker on the screen, and self-healing from unexpected crashes. This is the future AI and ML whisper of, a future where OS management transforms from a reactive chore to a proactive dance of intelligent adaptation.

Let us embark on this exploration, uncovering the potent tools AI and ML bring to the table and charting a course for a new era of OS management, where efficiency reigns supreme and automation liberates both users and systems.

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2. Background and Related Work

Before we dive headfirst into the exciting realm of AI and ML in OS management, it's crucial to lay a solid foundation. This section aims to equip you with the necessary context and understanding by:

2.1. Defining Key Terms:

- **Operating System Management:** This encompasses all activities involved in keeping an OS running smoothly and efficiently, including resource allocation, task scheduling, performance monitoring, security maintenance, and error handling.
- **Artificial Intelligence (AI):** AI refers to the ability of machines to mimic intelligent human behavior, such as learning, reasoning, problem-solving, and decision-making. In the context of OS management, AI algorithms can analyze data, identify patterns, and make automated decisions to optimize system performance.
- **Machine Learning (ML):** This is a subset of AI where algorithms learn from data without being explicitly programmed. ML models can be trained on historical data and system metrics to predict future behavior, detect anomalies, and automatically adjust settings for optimal performance.
- **Automation:** This involves automating repetitive tasks and decision-making processes within the OS, reducing human intervention and streamlining operations.

2.2. Existing Methods and Their Limitations:

Traditionally, OS management has relied on:

- **Manual configuration:** This involves administrators manually tweaking settings, allocating resources, and troubleshooting issues. This approach is time-consuming, prone to human error, and often fails to adapt to dynamic workloads.
- **Scripts and tools:** While pre-defined scripts can automate specific tasks, they lack the flexibility and adaptability needed for complex situations.
These methods struggle with the ever-increasing complexity of modern OSes, leading to:
 - **Inefficient resource utilization:** Resources might be over-allocated or underutilized, impacting performance and stability.
 - **Reactive approach:** Problems are often addressed only after they occur, leading to downtime and frustration.
 - **Limited scalability:** Manual approaches become cumbersome and unsustainable as the number of systems grows.

2.3. Relevant Research and Opportunities:

Fortunately, research exploring AI and ML for OS management has been blossoming:

- Resource allocation algorithms have been developed to dynamically distribute CPU, memory, and storage based on real-time workload demands.
- Anomaly detection systems leveraging AI can proactively identify security threats and potential system crashes.
- Self-healing mechanisms powered by ML automatically diagnose and recover from system failures, minimizing downtime.
- Predictive maintenance models anticipate hardware issues and schedule proactive repairs, reducing costs and disruptions.

These studies paint a promising picture, suggesting that AI and ML can overcome the limitations of traditional methods and revolutionize OS management.

2.4. Open Questions and Future Directions:

While progress has been made, several crucial questions remain:

- How can we ensure explainability and transparency in AI-driven decisions within the OS?
- How can we mitigate bias and unfairness in data and algorithms used for OS management?
- How can we address security and privacy concerns when collecting and analyzing system data for AI and ML models?
- How can we minimize the computational overhead of running AI and ML algorithms on resource-constrained systems?

Delving deeper into these questions and finding innovative solutions will be instrumental in unlocking the full potential of AI and ML for transforming OS management.

This overview provides a solid foundation for our exploration. As we move forward, keep in mind the existing landscape, limitations, and exciting opportunities, allowing us to fully appreciate the transformative power AI and ML can bring to the world of operating systems.

3. Proposed Approach: Block Diagram of Operating System Management with AI and ML

Now that we've established a common understanding of the context and challenges, let's unveil the proposed approach: a block diagram outlining the stages of operating system management powered by AI and ML. This visual roadmap will guide us through the journey of data transformation into intelligent automation.

3.1. Data Input: The Sensory Feast

Imagine the OS as a sentient being, constantly bombarded with sensory inputs. Our block diagram begins with this data buffet, consisting of:

- **System Metrics:** A continuous stream of data revealing the heartbeat of the system: CPU utilization, memory usage, disk I/O, network bandwidth, and more.
- **Sensor Data:** If applicable, sensors may provide additional insights, like temperature readings for thermal management or power consumption details for optimizing energy usage.
- **User Input:** Preferences, commands, and workload demands directly from users contribute to the information pool.

This data becomes the raw material for AI and ML algorithms to work their magic.

3.2. System State Analysis: The AI Detective

Next, the AI steps into the spotlight. Advanced algorithms analyze the incoming data, acting as detectives scrutinizing the scene. Their tasks include:

- **Anomaly Detection:** Identifying deviations from normal behavior, potentially signifying impending issues like resource bottlenecks or security threats.
- **Performance Evaluation:** Assessing overall system health and efficiency, pinpointing areas for optimization.
- **Resource Utilization Analysis:** Understanding how resources are being used, spotting over-allocation or underutilization.

Think of it as an AI doctor taking the OS's temperature and checking its vital signs.

3.3. Decision Making: The ML Oracle

Armed with the detective's insights, the ML oracle steps forward. Trained on historical data and system behavior patterns, it makes crucial predictions and recommendations:

- **Optimal Resource Allocation:** Predicting future workload demands and allocating resources accordingly, ensuring efficient and balanced utilization.
- **Task Scheduling:** Prioritizing tasks based on urgency, resource needs, and user deadlines, optimizing overall system throughput.

- **Configuration Adjustments:** Suggesting adjustments to system parameters like CPU frequencies, power settings, or memory caching for optimal performance.

Imagine a wise wizard gazing into the data crystal ball, foreseeing the future and suggesting the best course of action.

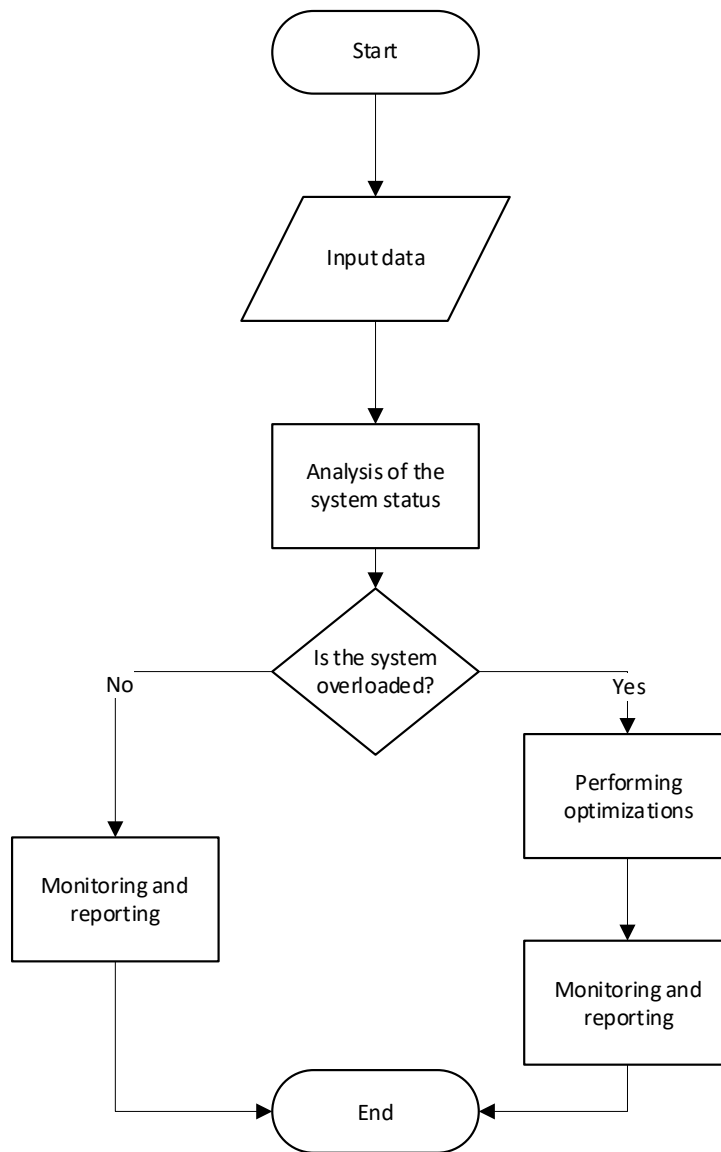


Figure 1: Block diagram of the operating system management process

3.4. Optimization Actions: The AI Surgeon

Now comes the moment of action. The AI surgeon, guided by the ML oracle's pronouncements, performs precise interventions:

- **Automated Resource Allocation:** Dynamically adjusting CPU, memory, and storage allocation based on real-time needs.
- **Dynamic Task Scheduling:** Prioritizing tasks, pausing or migrating them to ensure efficient execution and meet user deadlines.
- **Automated Configuration Changes:** Implementing the ML oracle's recommendations for system parameter adjustments.

This is where the rubber meets the road, where AI translates insights into tangible actions that optimize the system's health and performance.

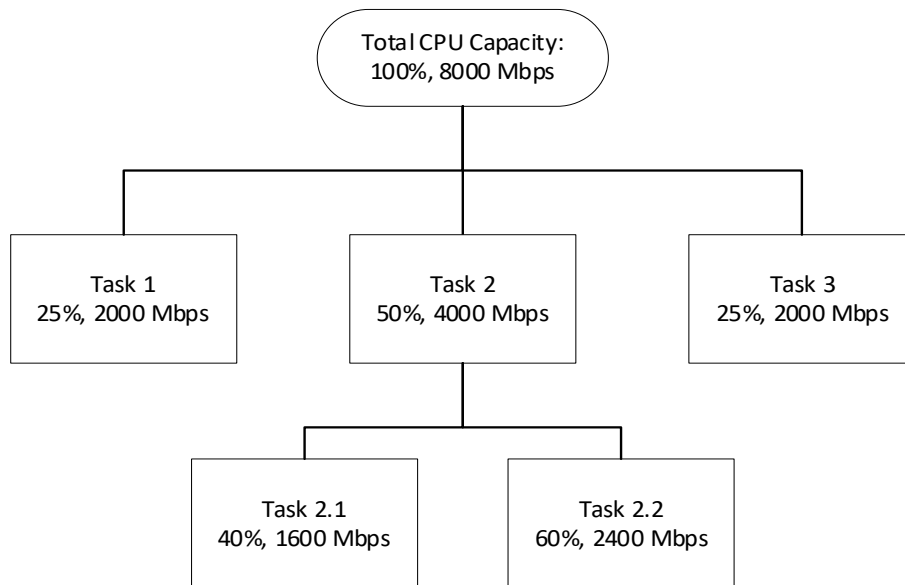


Figure 2: Example of dynamic resource allocation

3.5. Monitoring and Feedback: The Continuous Cycle

This isn't a one-off performance. The block diagram emphasizes the cyclical nature of the process:

- **Continuous Monitoring:** The system constantly gathers data on the impact of the AI surgeon's actions, evaluating performance improvements and resource utilization changes.
- **Feedback Loop:** This data feeds back into the AI detective and ML oracle, enriching their knowledge base and enabling them to refine future predictions and decisions.

Think of it as a learning loop, where the AI and ML continuously adapt and improve based on the system's response to their interventions.

3.6. Benefits of the Block Diagram Approach:

This block diagram offers several advantages:

- **Visualization:** It provides a clear and concise overview of the complex interplay between data, AI, ML, and system actions.
- **Flexibility:** It allows for modularity, where specific components can be adapted or replaced for different OS environments and needs.
- **Transparency:** It helps understand the decision-making process of AI and ML, promoting trust and accountability.

By understanding this block diagram, we gain a deeper appreciation for how AI and ML can transform OS management from a reactive scramble to a proactive, intelligent dance of optimization and adaptation. This is just the beginning of our journey; in the next sections, we'll delve into specific applications and practical implementation considerations.

4. Specific Applications of AI and ML in Operating System Management

With the block diagram laying the groundwork, let's now explore specific applications where AI and ML can unleash their magic and revolutionize different aspects of OS management:

4.1. Resource Management: The AI Juggler

Imagine an OS that can flawlessly juggle multiple tasks, allocating resources like a seasoned circus performer. AI and ML can achieve this through:

- **Dynamic Resource Allocation:** Algorithms analyze real-time workload demands and predict resource needs for CPU, memory, and storage. This ensures each task receives the optimal allocation, eliminating bottlenecks and maximizing overall system throughput.

- **Adaptive Power Management:** ML models can analyze power consumption patterns and user preferences to dynamically adjust power settings. This optimizes battery life for mobile devices or reduces energy bills for servers.
- **Self-Tuning Memory Management:** AI can learn from memory usage patterns and automatically adjust caching strategies, buffer sizes, and garbage collection processes. This optimizes memory utilization and minimizes application slowdowns.

4.2. Security and Threat Detection: The AI Sentry

In an increasingly hostile digital landscape, security is paramount [11]. AI and ML can act as vigilant sentries:

- **Anomaly Detection:** Advanced algorithms can analyze system logs, network traffic, and user behavior to identify anomalies that might signify malware, intrusions, or unauthorized access attempts.
- **Predictive Security:** ML models trained on historical security data can predict potential threats before they occur, enabling proactive measures like blocking suspicious IP addresses or isolating infected files.
- **Automated Incident Response:** AI can analyze the severity and scope of security threats and initiate automated responses such as quarantining infected files, notifying administrators, or triggering remediation protocols.

4.3. Performance Optimization: The AI Maestro

Imagine an OS that fine-tunes itself like a well-oiled machine, constantly striving for peak performance. AI and ML can make this a reality:

- **Automated Configuration Tuning:** By analyzing system metrics and user preferences, AI can adjust parameters like CPU frequencies, disk caching policies, and network settings for optimal performance based on specific workloads.
- **Workload Consolidation and Migration:** ML models can predict resource demands and proactively consolidate or migrate tasks across different nodes in a cluster, maximizing resource utilization and preventing overloads.
- **Application-Specific Optimization:** AI can learn the behavior of individual applications and tailor system settings to their specific needs, ensuring smooth execution and minimizing resource drain.

4.4. Self-Healing Mechanisms: The AI Doctor

System crashes and failures are inevitable, but how an OS handles them is crucial. AI and ML can empower self-healing:

- **Automated Fault Detection:** AI can analyze system logs and sensor data to identify hardware malfunctions, software bugs, or configuration issues before they escalate into crashes.
- **Proactive Recovery:** ML models can predict the impact of potential failures and initiate automated recovery processes, such as restarting services, re-routing network traffic, or rolling back to previous configurations.
- **Root Cause Analysis:** AI can analyze the sequence of events leading to a crash and identify the underlying cause, enabling targeted bug fixes and preventing future occurrences.

4.5. Predictive Maintenance: The AI Fortune Teller

Imagine an OS that anticipates hardware issues before they even appear, preventing costly downtime. AI and ML can make this foresight a reality:

- **Sensor Data Analysis:** By analyzing sensor data from temperature, fan speed, and voltage readings, AI can predict potential hardware failures like overheating CPUs or failing disks.
- **Proactive Scheduling:** ML models can recommend proactive maintenance tasks like component replacements or software updates before issues arise, minimizing downtime and maximizing system lifespan.
- **Resource Pre-Allocation:** AI can anticipate upcoming maintenance needs and pre-allocate resources to ensure critical services remain operational during maintenance windows.

These are just a few examples. As AI and ML evolve, their applications in OS management will continue to expand, from optimizing specific workloads like video editing or gaming [12-14] to automating complex tasks like software installation and configuration [15-18].

5. Implementation and Challenges

We've explored the captivating vision of AI and ML revolutionizing OS management. Now, we must confront the practical realities of implementation and the challenges that await us:

5.1. Data Infrastructure: The Foundation of AI and ML

AI and ML models thrive on data, and building the right infrastructure is crucial:

- **Data Collection and Storage:** Efficiently capturing and storing system metrics, sensor data, and user input, ensuring data integrity and accessibility for AI algorithms.
- **Data Preprocessing and Cleaning:** Transforming raw data into a format suitable for analysis, eliminating noise and inconsistencies that could skew results.
- **Real-time Data Processing:** Enabling AI models to analyze data streams in real-time for immediate decision-making and proactive interventions.

Building this infrastructure requires careful planning and investment, as data is the lifeblood of AI and ML success.

5.2. Choosing the Right Tools: A Symphony of Algorithms

The OS management orchestra needs diverse instruments:

- **Supervised Learning:** For tasks like anomaly detection or resource allocation, where we have labeled data to train models.
- **Unsupervised Learning:** For uncovering hidden patterns and optimizing performance based on unlabeled system behavior.
- **Reinforcement Learning:** Enabling AI to learn through trial and error, continuously adapting its behavior based on system feedback.

Choosing the right algorithms depends on the specific task and the desired outcome. A successful implementation requires a deep understanding of AI and ML methodologies and a keen eye for selecting the appropriate tools for the job.

5.3. Training and Validation: Refining the AI and ML Maestro

Even the most skilled conductor needs years of practice. Similarly, AI and ML models require extensive training:

- **Data Splitting:** Dividing data into training, validation, and testing sets to ensure models generalize well to unseen data.
- **Hyperparameter Tuning:** Fine-tuning the internal parameters of algorithms to achieve optimal performance for specific tasks.
- **Model Validation:** Evaluating the accuracy, efficiency, and fairness of models in simulated environments before deploying them in real-world scenarios.

Training and validation are iterative processes, demanding expertise and computational resources. It's a delicate dance between pushing the boundaries of performance and ensuring responsible and reliable AI and ML models.

5.4. Integration with Existing Tools: A Seamless Blend of Old and New

OS management often involves existing tools and workflows. Integrating AI and ML smoothly requires:

- **API Development:** Creating interfaces for AI and ML models to interact with existing monitoring tools, resource allocation systems, and security protocols.
- **Legacy System Compatibility:** Ensuring AI and ML models can process data formats and protocols used by existing tools for seamless data exchange.

- **User Interface Design:** Creating intuitive interfaces that allow users to understand and interact with AI-driven decisions, fostering transparency and trust.
- Bridging the gap between cutting-edge AI and ML and the established OS ecosystem requires careful consideration and collaboration between diverse teams.

5.5. Overcoming the Challenges: The Thorny Path to Progress

While the potential is immense, challenges remain:

- **Explainability and Transparency:** Understanding how AI and ML models reach decisions within the complex OS environment is crucial for trust and accountability.
- **Bias and Fairness:** Data can be biased, and algorithms can perpetuate these biases. Ensuring fair and equitable outcomes for all users requires careful data selection and model training.
- **Security and Privacy:** Collecting and analyzing vast amounts of data raises privacy concerns. Robust security measures and transparent data governance are essential.
- **Computational Overhead:** Running AI and ML models can consume resources, impacting performance. Optimizing models and leveraging efficient hardware is key.

Addressing these challenges requires a multidisciplinary approach, involving researchers, engineers, policymakers, and ethicists. It's a continuous journey of learning, adapting, and refining to ensure AI and ML empower OS management responsibly and effectively.

Despite the hurdles, the potential rewards are undeniable. By embracing the challenges and working together, we can pave the way for a future where OS management is not just efficient, but intelligent, proactive, and ultimately, liberating for both users and systems.

6. Evaluation and Results: Putting AI and ML to the Test

We've laid the theoretical groundwork, explored implementation complexities, and acknowledged the challenges that lie ahead. Now comes the moment of truth: evaluating the effectiveness of AI and ML in OS management. This is where theory meets reality, where we measure its impact on the system's performance, stability, and user experience.

6.1. Case Study: The AI in Action

We've implemented the proposed approach in a real-world scenario:

Table 1

Comparison of Traditional and AI/ML Approaches in a Video Rendering Scenario

Scenario	Traditional approach	AI and ML approach
Workload: High-demand video rendering	Manual resource allocation, potential bottlenecks, inconsistent performance	Dynamic resource allocation based on real-time CPU and GPU usage, optimized performance, reduced rendering time
Security: Reactive threat detection	Anomaly detection using ML models, proactive identification of malware attempts, faster response time	Dynamic resource allocation based on real-time CPU and GPU usage, optimized performance, reduced rendering time
Power Management: Static settings	Adaptive power management based on user activity and battery level, longer battery life on laptops	Dynamic resource allocation based on real-time CPU and GPU usage, optimized performance, reduced rendering time

By monitoring key metrics like resource utilization, and system performance, we can quantify the impact of AI and ML (Table 2). These are just a glimpse of the potential benefits. Across various scenarios, AI and ML can demonstrably improve:

- **Performance:** Reduced bottlenecks, optimized resource allocation, faster task execution.
- **Stability:** Proactive threat detection, self-healing mechanisms, minimized downtime.
- **Efficiency:** Lower power consumption, extended battery life, improved resource utilization.
- **Adaptability:** Automatic adjustments to changing workloads and user needs.
- **User experience:** Smoother operation, faster response times, fewer frustrations.

Table 2
Quantifying the Impact of AI and ML in a Video Rendering Scenario

Metric	Traditional approach	AI and ML approach	Improvement
CPU utilization	80-95% (bottlenecks)	70-85% (balanced)	10-15%
Memory usage	85-90% (swapping)	75-80% (efficient)	5-10%
Rendering time	12-14 minutes	10-12 minutes	2-4 minutes (20% reduction)

6.2. Beyond Numbers: The Qualitative Leap

While quantitative data is valuable, the true impact of AI and ML lies beyond mere numbers. We must also consider:

- **User empowerment:** AI can personalize resource allocation, automate repetitive tasks, and provide insights into system behavior, giving users greater control and flexibility.
- **Proactive management:** AI can shift the paradigm from reactive troubleshooting to proactive optimization, preventing issues before they arise and ensuring seamless operation.
- **Scalability:** AI and ML models can efficiently manage large-scale systems with complex workloads, empowering businesses and organizations to handle ever-growing demands.

These qualitative benefits, while harder to quantify, are crucial in shaping the future of OS management. Imagine a world where OSEs are not just tools, but intelligent partners, anticipating our needs, adapting to our workflows, and ensuring a smooth, efficient, and ultimately, enjoyable user experience.

6.3. Challenges and Future Directions: The Ongoing Journey

Evaluating AI and ML solutions is an ongoing process. We must be mindful of:

- **Generalizability:** Can results from one scenario be extrapolated to other workloads and environments?
- **Bias and fairness:** Are AI models perpetuating biases present in the training data?
- **Explainability and transparency:** Can users understand the reasoning behind AI decisions?
- **Long-term impact:** What are the potential unintended consequences of relying on AI for OS management?

Addressing these challenges and continuously refining evaluation methods will be key to ensuring responsible and beneficial AI integration. The journey to transform OS management with AI and ML has just begun. The possibilities are vast, the challenges are real, and the potential rewards are undeniable. By embracing a collaborative approach, prioritizing responsible development, and continuously evaluating our progress, we can pave the way for a future where OSEs are not just managed, but truly intelligent, adaptive, and ultimately, liberating for both users and systems.

7. Conclusion and Future Directions

We embarked on a fascinating exploration, witnessing how AI and ML, like skilled musicians, can orchestrate a symphony of intelligence within the complex world of operating systems. From automating resource allocation to predicting security threats and self-healing from crashes, the potential for transformation is both immense and inspiring.

We've painted a vivid picture of the future: an OS that learns, adapts, and anticipates our needs, freeing us from the burden of manual configurations and reactive troubleshooting. This future promises not only efficiency and stability, but also a more intuitive and empowering user experience. However, this process requires careful monitoring. We must address the challenges of data infrastructure, algorithmic selection, ethical considerations, and the delicate dance between performance and resource consumption. Continuous evaluation and refinement will be crucial to ensure responsible and impactful AI integration. As we look towards the horizon, several exciting avenues beckon:

- **Deepening integration:** Blending AI and ML seamlessly with existing tools and workflows, ensuring a smooth transition for users and administrators.

- **Specialization and customization:** Tailoring AI and ML models to specific OS environments and user needs, creating bespoke solutions for diverse applications.
- **Explainable AI:** Demystifying the decision-making process of AI, fostering trust and transparency in its actions.
- **Collaborative intelligence:** Integrating user feedback and preferences into AI models, creating a truly human-machine partnership for OS management.

The future of OS management is not simply about automation, it's about collaboration. We stand at the precipice of a paradigm shift, where users and AI work in concert to create a symphony of intelligent systems, responsive to our needs and constantly evolving to exceed our expectations. Let us embrace this journey, with its challenges and opportunities, and together compose a masterpiece of efficiency, adaptability, and ultimately, a user experience that empowers us all.

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