

AI FOR NUCLEAR PHYSICS

AI FOR NUCLEAR PHYSICS: REVOLUTIONIZING RESEARCH AND DISCOVERY

INTRODUCTION

AI FOR NUCLEAR PHYSICS IS RAPIDLY TRANSFORMING THE LANDSCAPE OF FUNDAMENTAL RESEARCH, OFFERING UNPRECEDENTED CAPABILITIES TO ANALYZE COMPLEX DATA, SIMULATE INTRICATE PHENOMENA, AND ACCELERATE DISCOVERY IN WAYS PREVIOUSLY UNIMAGINABLE. THIS SYNERGISTIC RELATIONSHIP BETWEEN ARTIFICIAL INTELLIGENCE AND THE STUDY OF ATOMIC NUCLEI IS OPENING NEW FRONTIERS, FROM UNDERSTANDING THE FORCES THAT BIND MATTER TO EXPLORING THE ORIGINS OF THE UNIVERSE. WE'LL DELVE INTO THE MULTIFACETED APPLICATIONS OF AI IN NUCLEAR PHYSICS, EXPLORING HOW MACHINE LEARNING ALGORITHMS ARE BEING EMPLOYED TO SIFT THROUGH PETABYTES OF EXPERIMENTAL DATA, DEVELOP MORE ACCURATE THEORETICAL MODELS, AND EVEN DESIGN NOVEL EXPERIMENTS. PREPARE TO BE AMAZED AS WE UNCOVER HOW AI IS NOT JUST ASSISTING NUCLEAR PHYSICISTS BUT FUNDAMENTALLY REDEFINING THE PACE AND SCOPE OF THEIR INVESTIGATIONS.

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THE EVOLVING ROLE OF AI IN NUCLEAR PHYSICS

THE SHEER VOLUME AND COMPLEXITY OF DATA GENERATED BY MODERN NUCLEAR PHYSICS EXPERIMENTS, SUCH AS THOSE AT PARTICLE ACCELERATORS AND LARGE-SCALE DETECTORS, PRESENT A FORMIDABLE CHALLENGE FOR TRADITIONAL ANALYSIS METHODS. THIS IS WHERE ARTIFICIAL INTELLIGENCE, PARTICULARLY MACHINE LEARNING, STEPS IN AS AN INDISPENSABLE TOOL. AI ALGORITHMS CAN IDENTIFY SUBTLE PATTERNS AND CORRELATIONS WITHIN MASSIVE DATASETS THAT MIGHT OTHERWISE GO UNNOTICED, SIGNIFICANTLY ENHANCING OUR ABILITY TO INTERPRET EXPERIMENTAL RESULTS. THINK OF IT LIKE A HIGHLY SOPHISTICATED DETECTIVE, SIFTING THROUGH MILLIONS OF CLUES TO FIND THE ONE CRUCIAL PIECE OF EVIDENCE THAT UNLOCKS A MYSTERY. THE INTEGRATION OF AI IS NOT MERELY AN INCREMENTAL IMPROVEMENT; IT REPRESENTS A PARADIGM SHIFT IN HOW NUCLEAR PHYSICISTS APPROACH THEIR RESEARCH, ENABLING THEM TO EXTRACT DEEPER INSIGHTS AND PUSH THE BOUNDARIES OF KNOWLEDGE.

BEYOND DATA ANALYSIS, AI IS ALSO PROVING INSTRUMENTAL IN DEVELOPING MORE EFFICIENT AND ACCURATE THEORETICAL FRAMEWORKS. BY LEARNING FROM EXISTING DATA AND ESTABLISHED PHYSICAL PRINCIPLES, AI MODELS CAN HELP REFINE THEORETICAL PREDICTIONS, SUGGEST NEW AVENUES FOR EXPLORATION, AND EVEN DISCOVER NOVEL PHYSICAL PHENOMENA. THIS ITERATIVE PROCESS, WHERE AI GUIDES BOTH EXPERIMENTAL AND THEORETICAL ENDEAVORS, CREATES A POWERFUL FEEDBACK LOOP THAT ACCELERATES THE SCIENTIFIC DISCOVERY PROCESS. THE FUTURE OF NUCLEAR PHYSICS IS UNDENIABLY INTERTWINED WITH THE CONTINUED ADVANCEMENT AND APPLICATION OF INTELLIGENT ALGORITHMS.

MACHINE LEARNING FOR PARTICLE IDENTIFICATION AND EVENT RECONSTRUCTION

ONE OF THE MOST IMMEDIATE AND IMPACTFUL APPLICATIONS OF AI IN NUCLEAR PHYSICS LIES IN THE REALM OF DATA PROCESSING, SPECIFICALLY FOR PARTICLE IDENTIFICATION AND EVENT RECONSTRUCTION. EXPERIMENTS AT FACILITIES LIKE THE LARGE HADRON COLLIDER (LHC) PRODUCE AN ASTONISHING NUMBER OF PARTICLE INTERACTIONS, EACH CONTAINING A WEALTH OF INFORMATION. DISTINGUISHING BETWEEN DIFFERENT TYPES OF PARTICLES (LIKE ELECTRONS, MUONS, PHOTONS, OR HADRONS) AND ACCURATELY RECONSTRUCTING THE TRAJECTORY AND ENERGY OF EACH PARTICLE WITHIN A COMPLEX DETECTOR SYSTEM IS CRUCIAL FOR UNDERSTANDING THE UNDERLYING PHYSICS. TRADITIONAL METHODS, WHILE ROBUST, CAN BE COMPUTATIONALLY INTENSIVE AND SOMETIMES STRUGGLE WITH THE SHEER DENSITY OF INFORMATION IN HIGH-ENERGY COLLISIONS.

MACHINE LEARNING ALGORITHMS, ESPECIALLY DEEP LEARNING TECHNIQUES LIKE CONVOLUTIONAL NEURAL NETWORKS (CNNs) AND RECURRENT NEURAL NETWORKS (RNNs), EXCEL AT PATTERN RECOGNITION IN HIGH-DIMENSIONAL DATA. FOR PARTICLE IDENTIFICATION, THESE NETWORKS CAN BE TRAINED ON SIMULATED AND EXPERIMENTAL DATA TO CLASSIFY PARTICLE SIGNATURES WITHIN DETECTOR SIGNALS WITH REMARKABLE ACCURACY AND SPEED. IMAGINE TRAINING A NETWORK TO RECOGNIZE THE UNIQUE "FINGERPRINT" OF AN ELECTRON BASED ON HOW IT INTERACTS WITH DIFFERENT LAYERS OF A DETECTOR – THIS IS PRECISELY WHAT AI CAN ACHIEVE. SIMILARLY, FOR EVENT RECONSTRUCTION, AI CAN LEARN TO ASSOCIATE SIGNALS FROM VARIOUS DETECTOR COMPONENTS TO TRACE THE PATHS OF PARTICLES, DETERMINE THEIR MOMENTA, AND RECONSTRUCT THE OVERALL EVENT TOPOLOGY.

THIS ENHANCED EFFICIENCY AND ACCURACY HAVE PROFOUND IMPLICATIONS. FASTER AND MORE PRECISE PARTICLE IDENTIFICATION MEANS THAT PHYSICISTS CAN ANALYZE LARGER DATASETS MORE QUICKLY, LEADING TO QUICKER VALIDATION OF THEORETICAL PREDICTIONS AND THE POTENTIAL TO DISCOVER RARE EVENTS THAT MIGHT HAVE BEEN MISSED BEFORE. EVENT RECONSTRUCTION, WHEN REFINED BY AI, ALLOWS FOR MORE DETAILED AND RELIABLE STUDIES OF FUNDAMENTAL PROCESSES, SUCH AS THE PRODUCTION AND DECAY OF EXOTIC PARTICLES. THIS ABILITY TO METICULOUSLY PIECE TOGETHER THE AFTERMATH OF SUBATOMIC COLLISIONS IS THE BEDROCK OF MUCH OF NUCLEAR AND PARTICLE PHYSICS RESEARCH.

AI-POWERED SIMULATIONS AND THEORETICAL MODELING

SIMULATING THE COMPLEX BEHAVIOR OF ATOMIC NUCLEI AND THE INTERACTIONS BETWEEN SUBATOMIC PARTICLES IS A CORNERSTONE OF NUCLEAR PHYSICS THEORY. HOWEVER, THESE SIMULATIONS CAN BE COMPUTATIONALLY DEMANDING, REQUIRING VAST AMOUNTS OF PROCESSING POWER AND TIME, ESPECIALLY WHEN EXPLORING EXOTIC NUCLEAR STATES OR THE CONDITIONS FOUND IN EXTREME ASTROPHYSICAL ENVIRONMENTS. AI IS EMERGING AS A POWERFUL ALLY IN THIS DOMAIN, OFFERING NOVEL WAYS TO ACCELERATE SIMULATIONS, IMPROVE THEIR ACCURACY, AND EVEN DISCOVER NEW THEORETICAL MODELS.

ONE SIGNIFICANT CONTRIBUTION OF AI IS IN THE DEVELOPMENT OF SURROGATE MODELS, OFTEN REFERRED TO AS "EMULATORS." THESE AI MODELS ARE TRAINED ON THE OUTPUTS OF COMPUTATIONALLY EXPENSIVE TRADITIONAL SIMULATIONS. ONCE TRAINED, THE AI EMULATOR CAN PREDICT SIMULATION RESULTS ALMOST INSTANTANEOUSLY, ALLOWING PHYSICISTS TO EXPLORE A MUCH WIDER PARAMETER SPACE AND PERFORM SENSITIVITY ANALYSES MUCH MORE EFFICIENTLY. INSTEAD OF RUNNING A SINGLE, LENGTHY SIMULATION, RESEARCHERS CAN USE AN AI EMULATOR TO RAPIDLY GENERATE THOUSANDS OF RESULTS, PROVIDING A COMPREHENSIVE UNDERSTANDING OF HOW DIFFERENT PARAMETERS INFLUENCE THE OUTCOME.

FURTHERMORE, AI CAN BE USED TO OPTIMIZE THE PARAMETERS OF EXISTING THEORETICAL MODELS. BY EMPLOYING OPTIMIZATION ALGORITHMS GUIDED BY MACHINE LEARNING, PHYSICISTS CAN FINE-TUNE MODELS TO BETTER MATCH EXPERIMENTAL DATA, LEADING TO MORE ACCURATE PREDICTIONS. THIS IS PARTICULARLY USEFUL IN AREAS LIKE NUCLEAR STRUCTURE THEORY, WHERE MANY-BODY INTERACTIONS MAKE ANALYTICAL SOLUTIONS DIFFICULT TO OBTAIN. AI CAN ALSO HELP IN THE DISCOVERY OF ENTIRELY NEW THEORETICAL RELATIONSHIPS OR APPROXIMATIONS BY IDENTIFYING UNDERLYING PATTERNS IN DATA THAT MIGHT SUGGEST NOVEL PHYSICAL PRINCIPLES OR SIMPLIFICATIONS. THIS ABILITY TO AUGMENT AND EVEN INSPIRE THEORETICAL DEVELOPMENT IS A TESTAMENT TO AI'S TRANSFORMATIVE POTENTIAL IN PUSHING THE FRONTIERS OF OUR UNDERSTANDING OF THE NUCLEAR REALM.

APPLICATIONS OF AI IN NUCLEAR ASTROPHYSICS

THE UNIVERSE ITSELF IS A GRAND LABORATORY FOR NUCLEAR PHYSICS, AND AI IS PLAYING AN INCREASINGLY VITAL ROLE IN UNRAVELING ITS MOST PROFOUND MYSTERIES. NUCLEAR ASTROPHYSICS SEEKS TO UNDERSTAND THE ORIGIN AND EVOLUTION OF THE ELEMENTS, THE PROCESSES POWERING STARS, AND THE NATURE OF EXTREME COSMIC EVENTS LIKE SUPERNOVAE AND NEUTRON STAR MERGERS. THESE PHENOMENA INVOLVE NUCLEAR REACTIONS OCCURRING UNDER CONDITIONS OF IMMENSE TEMPERATURE, PRESSURE, AND DENSITY, MAKING THEM INCREDIBLY CHALLENGING TO STUDY.

ONE KEY AREA WHERE AI IS MAKING A DIFFERENCE IS IN ANALYZING DATA FROM ASTRONOMICAL OBSERVATIONS. TELESCOPES AND OBSERVATORIES GATHER VAST AMOUNTS OF INFORMATION ABOUT THE COMPOSITION, TEMPERATURE, AND DYNAMICS OF CELESTIAL OBJECTS. AI ALGORITHMS CAN SIFT THROUGH THIS DATA TO IDENTIFY SPECTRAL SIGNATURES OF SPECIFIC ISOTOPES, CLASSIFY DIFFERENT TYPES OF COSMIC EVENTS, AND EVEN DETECT FAINT SIGNALS THAT MIGHT INDICATE NEW ASTROPHYSICAL PROCESSES. FOR INSTANCE, AI CAN BE TRAINED TO RECOGNIZE THE UNIQUE LIGHT CURVES OR SPECTRAL FEATURES ASSOCIATED WITH SPECIFIC NUCLEOSYNTHESIS PATHWAYS, HELPING ASTROPHYSICISTS PINPOINT WHERE AND HOW HEAVY ELEMENTS ARE FORGED.

MOREOVER, AI IS INSTRUMENTAL IN IMPROVING THE ACCURACY OF SIMULATIONS OF STELLAR EVOLUTION AND EXPLOSIVE ASTROPHYSICAL EVENTS. THESE SIMULATIONS OFTEN RELY ON DETAILED NUCLEAR REACTION NETWORKS, WHICH CAN INVOLVE THOUSANDS OF ISOTOPES AND REACTIONS. AI CAN HELP TO OPTIMIZE THESE NETWORKS, PREDICT THE YIELDS OF SPECIFIC ELEMENTS FROM STELLAR PROCESSES, AND EXPLORE A WIDER RANGE OF ASTROPHYSICAL SCENARIOS. THE ABILITY OF AI TO PROCESS COMPLEX OBSERVATIONAL DATA AND ENHANCE THEORETICAL SIMULATIONS ALLOWS NUCLEAR ASTROPHYSICISTS TO GAIN A MORE COMPREHENSIVE AND ACCURATE PICTURE OF HOW THE ELEMENTS THAT MAKE UP EVERYTHING AROUND US CAME TO BE, FROM THE BIG BANG TO THE HEARTS OF STARS.

AI FOR NUCLEAR ENERGY AND REACTOR DESIGN

THE APPLICATION OF AI EXTENDS BEYOND FUNDAMENTAL RESEARCH INTO PRACTICAL DOMAINS LIKE NUCLEAR ENERGY. ENSURING THE SAFETY, EFFICIENCY, AND SUSTAINABILITY OF NUCLEAR POWER GENERATION IS PARAMOUNT, AND AI OFFERS POWERFUL TOOLS TO ADDRESS THESE CHALLENGES. FROM OPTIMIZING REACTOR OPERATIONS TO PREDICTING MATERIAL DEGRADATION AND ENHANCING SAFETY PROTOCOLS, AI IS POISED TO REVOLUTIONIZE THE NUCLEAR ENERGY SECTOR.

IN THE REALM OF REACTOR DESIGN AND OPERATION, AI CAN BE USED TO DEVELOP SOPHISTICATED CONTROL SYSTEMS. MACHINE LEARNING ALGORITHMS CAN LEARN FROM OPERATIONAL DATA TO PREDICT AND OPTIMIZE FUEL BURNUP, MANAGE THERMAL HYDRAULICS, AND ENSURE STABLE REACTOR PERFORMANCE. THIS LEADS TO INCREASED EFFICIENCY AND REDUCED OPERATIONAL COSTS. AI-POWERED PREDICTIVE MAINTENANCE IS ALSO A GAME-CHANGER. BY ANALYZING SENSOR DATA FROM VARIOUS REACTOR COMPONENTS, AI CAN DETECT SUBTLE ANOMALIES THAT MAY INDICATE IMPENDING FAILURES, ALLOWING FOR TIMELY MAINTENANCE AND PREVENTING COSTLY DOWNTIME OR SAFETY INCIDENTS. IMAGINE AN AI SYSTEM THAT CAN LISTEN TO THE "HEALTH" OF A REACTOR, ALERTING OPERATORS TO POTENTIAL ISSUES BEFORE THEY BECOME CRITICAL.

SAFETY IS, OF COURSE, THE TOP PRIORITY IN NUCLEAR ENERGY. AI CAN SIGNIFICANTLY ENHANCE SAFETY BY ANALYZING VAST AMOUNTS OF DATA FROM SAFETY MONITORING SYSTEMS TO IDENTIFY POTENTIAL RISKS AND ANOMALIES. IT CAN ALSO ASSIST IN EMERGENCY RESPONSE PLANNING AND EVEN AUTONOMOUS DECISION-MAKING IN CERTAIN CRITICAL SCENARIOS, PROVIDING OPERATORS WITH CRUCIAL SUPPORT DURING HIGH-STRESS SITUATIONS. FURTHERMORE, AI IS BEING EMPLOYED IN THE DEVELOPMENT OF ADVANCED REACTOR DESIGNS, SUCH AS SMALL MODULAR REACTORS (SMRs), BY OPTIMIZING THEIR CONFIGURATIONS AND SIMULATING THEIR PERFORMANCE UNDER VARIOUS CONDITIONS. THE INTEGRATION OF AI PROMISES TO MAKE NUCLEAR ENERGY SAFER, MORE RELIABLE, AND MORE EFFICIENT FOR GENERATIONS TO COME.

CHALLENGES AND FUTURE DIRECTIONS FOR AI IN NUCLEAR PHYSICS

DESPITE THE IMMENSE PROGRESS AND PROMISE, THE INTEGRATION OF AI IN NUCLEAR PHYSICS IS NOT WITHOUT ITS CHALLENGES.

ONE SIGNIFICANT HURDLE IS THE INTERPRETABILITY OF COMPLEX AI MODELS. WHILE DEEP LEARNING NETWORKS CAN ACHIEVE REMARKABLE ACCURACY, UNDERSTANDING PRECISELY WHY THEY MAKE CERTAIN PREDICTIONS CAN BE DIFFICULT, A PHENOMENON OFTEN REFERRED TO AS THE "BLACK BOX" PROBLEM. IN A FIELD LIKE NUCLEAR PHYSICS, WHERE A DEEP UNDERSTANDING OF UNDERLYING PHYSICAL PRINCIPLES IS CRUCIAL, THE LACK OF INTERPRETABILITY CAN BE A SIGNIFICANT CONCERN FOR VALIDATING SCIENTIFIC FINDINGS. DEVELOPING MORE EXPLAINABLE AI (XAI) TECHNIQUES WILL BE CRITICAL FOR BUILDING TRUST AND FACILITATING DEEPER SCIENTIFIC INSIGHT.

ANOTHER CHALLENGE IS THE NEED FOR HIGH-QUALITY, WELL-LABELED TRAINING DATA. WHILE NUCLEAR PHYSICS EXPERIMENTS GENERATE VAST AMOUNTS OF DATA, CREATING CURATED DATASETS THAT ARE SUITABLE FOR TRAINING AI MODELS OFTEN REQUIRES SIGNIFICANT HUMAN EFFORT AND EXPERTISE. FURTHERMORE, GENERALIZING AI MODELS TO ENTIRELY NEW EXPERIMENTAL REGIMES OR THEORETICAL FRAMEWORKS CAN BE DIFFICULT, REQUIRING CAREFUL VALIDATION AND RETRAINING. THE DEVELOPMENT OF ROBUST AI ARCHITECTURES THAT CAN ADAPT TO NOVEL SITUATIONS AND THE CREATION OF STANDARDIZED BENCHMARKS FOR AI PERFORMANCE IN NUCLEAR PHYSICS ARE ACTIVE AREAS OF RESEARCH.

LOOKING AHEAD, THE FUTURE OF AI IN NUCLEAR PHYSICS IS INCREDIBLY EXCITING. WE CAN ANTICIPATE AI PLAYING AN EVEN LARGER ROLE IN EXPERIMENTAL DESIGN, SUGGESTING OPTIMAL CONFIGURATIONS FOR DETECTORS OR PARTICLE BEAMS TO MAXIMIZE SCIENTIFIC OUTPUT. AI COULD ALSO BECOME AN INTEGRAL PART OF AUTOMATED ANALYSIS PIPELINES, ENABLING NEAR REAL-TIME INSIGHTS FROM EXPERIMENTS. THE SYNERGY BETWEEN AI AND QUANTUM COMPUTING HOLDS PARTICULAR PROMISE, POTENTIALLY UNLOCKING THE ABILITY TO SIMULATE MUCH LARGER AND MORE COMPLEX NUCLEAR SYSTEMS THAN EVER BEFORE. AS AI CONTINUES TO EVOLVE, ITS PARTNERSHIP WITH NUCLEAR PHYSICS WILL UNDOUBTEDLY LEAD TO GROUNDBREAKING DISCOVERIES THAT RESHAPE OUR UNDERSTANDING OF THE UNIVERSE AT ITS MOST FUNDAMENTAL LEVEL.

FREQUENTLY ASKED QUESTIONS

Q: HOW DOES AI HELP IN IDENTIFYING DIFFERENT TYPES OF SUBATOMIC PARTICLES IN NUCLEAR PHYSICS EXPERIMENTS?

A: AI, PARTICULARLY MACHINE LEARNING ALGORITHMS LIKE NEURAL NETWORKS, IS TRAINED ON THE UNIQUE SIGNATURES THAT DIFFERENT PARTICLES LEAVE IN DETECTORS. THESE ALGORITHMS LEARN TO CLASSIFY PARTICLE TRACKS, ENERGY DEPOSITIONS, AND OTHER DETECTOR RESPONSES TO ACCURATELY DISTINGUISH BETWEEN PARTICLES LIKE ELECTRONS, MUONS, PHOTONS, AND HADRONS, EVEN IN VERY COMPLEX COLLISION EVENTS.

Q: CAN AI BE USED TO IMPROVE THE ACCURACY OF NUCLEAR PHYSICS SIMULATIONS?

A: YES, AI CAN SIGNIFICANTLY IMPROVE NUCLEAR PHYSICS SIMULATIONS IN SEVERAL WAYS. IT CAN BE USED TO CREATE FASTER "EMULATORS" THAT APPROXIMATE THE RESULTS OF COMPUTATIONALLY EXPENSIVE SIMULATIONS, ENABLING WIDER EXPLORATION OF PARAMETER SPACES. AI CAN ALSO OPTIMIZE PARAMETERS WITHIN EXISTING THEORETICAL MODELS TO BETTER MATCH EXPERIMENTAL DATA, LEADING TO MORE ACCURATE PREDICTIONS OF NUCLEAR BEHAVIOR.

Q: WHAT IS THE ROLE OF AI IN NUCLEAR ASTROPHYSICS AND UNDERSTANDING THE ORIGIN OF ELEMENTS?

A: IN NUCLEAR ASTROPHYSICS, AI ANALYZES ASTRONOMICAL OBSERVATION DATA TO IDENTIFY ELEMENTAL COMPOSITIONS AND CLASSIFY COSMIC EVENTS. IT ALSO ENHANCES SIMULATIONS OF STELLAR EVOLUTION AND EXPLOSIVE EVENTS LIKE SUPERNOVAE BY OPTIMIZING NUCLEAR REACTION NETWORKS AND PREDICTING ELEMENT YIELDS, HELPING SCIENTISTS UNDERSTAND HOW ELEMENTS ARE FORGED IN STARS AND THROUGHOUT THE UNIVERSE.

Q: HOW IS AI CONTRIBUTING TO THE DEVELOPMENT AND SAFETY OF NUCLEAR ENERGY

REACTORS?

A: AI IS USED FOR OPTIMIZING REACTOR OPERATIONS, DEVELOPING ADVANCED CONTROL SYSTEMS FOR EFFICIENCY, AND ENABLING PREDICTIVE MAINTENANCE BY DETECTING POTENTIAL COMPONENT FAILURES BEFORE THEY OCCUR. IT ALSO ENHANCES SAFETY BY ANALYZING MONITORING DATA FOR ANOMALIES AND ASSISTING IN EMERGENCY RESPONSE PLANNING, MAKING NUCLEAR ENERGY MORE RELIABLE AND SECURE.

Q: WHAT ARE THE MAIN CHALLENGES IN APPLYING AI TO NUCLEAR PHYSICS RESEARCH?

A: KEY CHALLENGES INCLUDE THE INTERPRETABILITY OF COMPLEX AI MODELS (THE "BLACK BOX" PROBLEM), THE NEED FOR LARGE, HIGH-QUALITY, AND WELL-LABELED TRAINING DATASETS, AND THE DIFFICULTY IN GENERALIZING AI MODELS TO ENTIRELY NEW SCIENTIFIC DOMAINS OR EXPERIMENTAL SETUPS WITHOUT EXTENSIVE RETRAINING AND VALIDATION.

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