Artificial Intelligence & Wireless Spectrum: Opportunities and Challenges

2019 Workshop Report

The Networking & Information Technology R&D Program
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Contents

Executive Summary

Fast and efficient wireless spectrum policy creation, adoption, and management are critical to maintaining U.S. leadership in the deployment of next-generation wireless technologies and ensuring national security. U.S. spectrum policy and management must adapt to trends such as evolving 5G technologies, novel wireless data network architectures, and security threats. Spectrum research and development (R&D) is essential to increase efficient and robust spectrum use, dynamically manage spectrum resources, optimize network design and operations, and enable wireless network security. Artificial intelligence (AI) techniques can provide key support to these R&D goals, including the use of AI to assist in operating and securing large complex networks more efficiently, automating dynamic spectrum management, and validating spectrum access. Significant R&D also addresses AI implementation challenges such as bias, uncertainty, reliability, and the data fidelity and availability that impact research.

The Wireless Spectrum R&D Interagency Working Group workshop, Artificial Intelligence and Wireless Spectrum: Opportunities and Challenges, was held in August 2019 to further explore the role of AI techniques to improve wireless spectrum use and management. The workshop underscored the opportunities and challenges facing next-generation wireless spectrum management. AI technologies appear to have high potential for the wireless spectrum domain. However, there are fundamental challenges that need to be addressed. For example, AI-based solutions need to be well-defined, supported by the appropriate datasets, and able to be verified and validated. Continual acquisition and appropriate use of trustworthy, validated data and datasets will be critical components of both the opportunities and the challenges AI presents to wireless spectrum policy and management.

Introduction

Artificial intelligence "enables computers and other automated systems to perform tasks that have historically required human cognition and what we typically consider human decision-making abilities."[1] Such tasks include planning, recognition, and autonomous decision making (e.g., weather prediction). Machine learning (ML) is a subfield of AI based on algorithms that improve automatically through experience. ML algorithms build mathematical models based on sample data, known as training data, in order to make predictions or decisions without being explicitly programmed to do so.

Wireless spectrum has been managed and utilized over many decades through a complex regulatory framework and a patchwork of policies. The current manual process of assessing spectrum needs is increasingly problematic due to the growing level of interdependencies in the spectrum domain. Existing and emerging methods for allocating spectrum are often driven by small studies that suffer from inherent biases. As a result, spectrum policies and usage are often suboptimal and rigid, preventing efficient use of wireless spectrum. The U.S. position as a global leader in advanced wireless technologies and deployment, including 5G networks, depends upon rapid and efficient policy creation, adoption, and spectrum management of wireless spectrum. AI has successfully been applied in domains such as image

[1] *The National Artificial Intelligence Research and Development Strategic Plan: 2019 Update*, https://www.nitrd.gov/pubs/National-AI-RD-Strategy-2019.pdf, p. 1.

classification, voice recognition, and autonomous navigation where previously a model-based approach[2] or a vital human-in-the-loop element had been used. For these applications, AI can scale beyond human capacities and approach the reliability of human cognition, and the judicious integration of AI techniques has the potential to provide similar gains in wireless spectrum engineering.

The Networking and Information Technology Research and Development (NITRD) Program's Wireless Spectrum R&D (WSRD) Interagency Working Group (IWG) held a workshop, *Artificial Intelligence and Wireless Spectrum: Opportunities and Challenges*,[3] on August 28–29, 2019, in Rome, New York. The purpose of this workshop was to identify areas where AI techniques, including ML, can help increase efficiency of wireless spectrum use and to discuss ongoing spectrum management research that utilizes AI techniques. The workshop brought together government, academic, and industry stakeholders to discuss current and potential use cases and help identify where further research is needed.

To help structure and focus the workshop discussions, an expert panel explored the current state of AI as it relates to wireless spectrum, and workshop participants further discussed the following themes: AI for future communications networks, AI for dynamic spectrum allocation and policy management, and AI for spectrum sharing.

Current State of AI: Opportunities and Challenges

Several capabilities of AI technologies proven in other applications (e.g., image recognition, voice recognition, autonomous transportation, and financial market analysis) appear to have high potential for the wireless spectrum domain. AI-based approaches could contribute where the problems are very complex to model or have too many parameters for closed-form solution.[4] AI would be most useful in the following situations: (1) where behavior is nondeterministic or the deterministic nature of a problem is very complex to model, or (2) what to look for is unknown.

The types of data and the required capabilities guide the selection of different AI techniques for next-generation spectrum management, as shown in Table 1 below.

Table 1: AI techniques and their potential uses in spectrum management

AI Techniques	Use in Spectrum Management
Anomaly identification	Spectrum monitoring
Prediction	Spectrum diagnosis
Recommendation	Mitigation of interference
Translation	Network integration
Detection and classification	Spectrum sensing

[2] A model-based approach is when decisions are made from a static model that is not designed to learn or adapt as new or novel data is ingested and new patterns are detected. In contrast, an AI-based approach is designed to adapt to new data and patterns and optimize its decision or output.

[3] https://www.nitrd.gov/nitrdgroups/index.php?title=Artificial-Intelligence-Wireless-Spectrum

[4] A closed-form solution is an equation that solves a given problem in terms of mathematical operations and functions from a universally accepted set.

While recent applications of AI have led to vast improvements in AI capabilities, current AI technologies are at varying degrees of maturity and need further research to ensure their applicability across various problem and domain sets. In addition, the following open problems and concerns may be potential impediments to incorporating AI into spectrum management systems:

- Inability of current theory to explain or prevent failures in AI models
- Difficulty detecting spurious correlations in hidden data
- Limited understanding of human-AI system interactions
- Stability issues related to predictions if or as conditions change
- Interpretability of models
- Leveraging human feedback into the multidomain training/learning process
- Incorporation of information about physical environments into the training models

In order to apply AI to spectrum research problems, the researcher needs to start with the appropriate AI method and associated datasets that match the desired function. Research should start with basic, traditional, proactive, and predictive AI techniques that train on carefully selected data collections that build value propositions. A complex, multidimensional system such as wireless spectrum management requires a gradual transition to the use of AI. Proactive, predictive AI applications (as opposed to deep learning[5] and reactive systems) limit potential transition issues when moving from a manual spectrum management system to a fully autonomous AI-enabled one.

AI for Future Communications Networks

Communication networks and associated architectures are evolving into complex, heterogeneous, interconnected entities that are increasingly difficult to manage with traditional, model-based approaches. AI has the potential to assist in operating and securing large, complex networks, address emerging use cases and applications, and achieve end-to-end objectives. Workshop discussions focused on three communications network topics where there is maximum potential for AI usage: (1) dynamic network planning and resource allocation, (2) network monitoring and security, and (3) integrating increasingly heterogeneous wireless networks.

Dynamic Network Planning and Resource Allocation

Today's highly dynamic networks present key challenges to network control. While decades of improvements have led to finely tuned networks, there is an inability to rapidly converge on new optimum operation in dynamic network conditions.

To address this issue, the first place to start is to incorporate existing knowledge and tools for network optimization into current AI models. Because network control involves learned transactions, a reinforcement learning approach of learning "best actions" from network feedback will play a critical role in the research process. This research requires suitable network testing environments that enable both learning from and testing of AI solutions.

[5] Also known as deep neural learning or deep neural network, deep learning is an AI function that creates patterns for use in decision making. A subset of machine learning, deep learning uses multiple layers in the neural network to progressively extract higher-level features from raw input. For example, in image processing, lower layers may identify edges while higher layers may identify the concepts relevant to a human, such as digits or letters or faces.

Trustworthy network data that is continually refreshed for training, updating, and reinforcing AI's ability to learn about changes in the network environment are essential to ensure successful research outcomes. An overall incremental approach towards implementing workable AI solutions for network control would gradually build public trust in AI systems, with potentially higher levels of trust for extreme-environment systems (e.g., self-driving cars).

There is also a need to research incentives for intersystem communication where multiple network operators are involved. Given the relative sparsity of data from practical network instances, identifying the tradeoffs between incentives and network performance through an AI-driven exploration of the state space is key. Network function virtualization (i.e., decoupling of network functions from proprietary hardware appliances and running them as software in virtual machines) and the O-RAN Alliance project,[6] which is gaining momentum, may provide additional research opportunities.

Network Monitoring, Diagnosis, Mitigation, and Security

The challenge of coordinating networks that involve increasing heterogeneity, technologies, and spectrum calls for adaptive AI solutions for future wireless networks. The AI analog is treating these networks as multiagent systems that create more effective hybrid solutions (from optimization to game theory) than a single network solution. Determining where and at what level to apply AI solutions to wireless networks, however, is an open question. For example, it is yet unclear whether security for wireless networks requires novel AI techniques or if existing solutions would suffice. Practitioners need to identify unique problems that are unsolvable by current methods and avoid applying AI when existing techniques would suffice.

Another challenge is the significant absence of standardized datasets and the related need for clear, well-defined AI objectives and applications, especially when it relates to network optimization and security. Advanced wireless networks, such as 5G networks with their increased size and complexity, may be more difficult to optimize and more sensitive to malicious attacks. While AI-based solutions would be helpful for 5G networks, the selection of a short-term, long-term, or hybrid solution depends upon the AI objective. Another critical issue to research is whether poorly performing AI agents can be distinguished from a malicious attack containing poisoned data.

Heterogeneous Network Integration

Tighter integration of heterogeneous networks has been a network design goal for over two decades, and modern wireless devices can operate across multiple networks, often simultaneously. AI may further improve heterogeneous network integration in the areas of protocol compatibility and translation, network diagnostics, and the certification and compliance testing of network interfaces.

AI algorithms can help translate between different protocols from heterogeneous networks. AI prediction and mitigation of network issues may also be useful in network diagnostics. In addition, AI may help in certifying the behavior of AI systems within a prescribed parameter space as networks transition to incorporating more AI into their operations. Other network function areas that may benefit from AI include classification of transmission technology, traffic load prediction, intelligent selection of radio

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[6] The Open Radio Access Network Alliance was formed to "lead the industry towards open, interoperable interfaces and radio access network virtualization." The O-RAN project involves "embedded intelligence, applied at both component and network levels, to enable dynamic local radio resource allocation and optimize network-wide efficiency." https://www.o-ran.org

access technology and frequency, anomaly detection, and misconfiguration detection. Additionally, AI has the potential to provide adaptive/cooperative waveform-selection-based use of deep learning techniques on the physical layer with auto-encoders.

The AI training process presents another challenge due to the difficulty in obtaining data from the government or private industry for supervised learning. While testing through facilities such as Colosseum[7] and PAWR[8] generate rich datasets, more testing and validation is needed prior to deploying true AI heterogeneous networks. As noted throughout this report, participants identified an overarching need for improved datasets to support better learning and validation for defined AI objectives.

The evaluation process for comparing AI systems to traditional systems prior to deployment requires validation tools and criteria that do not currently exist. Certification of these networks will be difficult because they are dynamic, likely making traditional device certification procedures inapplicable. Potential solutions include the use of "fuzzy" algorithms that rely on a range of values, live monitoring to keep AI algorithm results within acceptable bounds, and using adversarial (more advanced) AI methods to test and certify the algorithms.

The challenge of connecting increasingly heterogeneous wireless networks mirrors the challenge of managing the wireless spectrum that these applications and networks depend upon.

AI for Dynamic Spectrum Allocation and Policy Management

The increasing demand for wireless spectrum has inspired innovation and major breakthroughs that make its use more effective and efficient, such as dynamic spectrum sharing. However, these advances have made traditional, labor-intensive spectrum allocation and policy management more difficult, if not obsolete. Workshop participants discussed three major areas related to the need for automation: (1) integrating AI into current spectrum tools and datasets, (2) using AI to learn using very large datasets and time horizons, and (3) using AI predictions for better spectrum allocation policies.

Integrating AI into Legacy Tools and Datasets

Integrating AI into current spectrum sensing, processing, and readout tools and datasets can improve spectrum management and the overall communications planning process. AI has the potential to improve both the reliability of predictive spectrum assignments through better training sets and the propagation algorithms used in the planning process. The use of AI could leverage and improve existing tools by focusing on specific areas, such as spectrum planning and real environment sensing, to improve dynamic spectrum access (DSA)[9] operations. Two key actions for advancing AI use in spectrum are:

- ***Create simulations using standardized training datasets*** that approximate real-life data and include privacy and scalability concerns.
- ***Use known wireless signal information from spectrum measurements*** to reduce the training overhead of AI models.

[7] https://www.northeastern.edu/colosseum/

[8] Platforms for Advanced Wireless Research program. https://www.advancedwireless.org/

[9] Dynamic spectrum access is a policy that provides the capability to share the wireless channel to the unlicensed users (i.e., secondary users) along with licensed users (primary users) in an opportunistic manner. https://www.igi-global.com/dictionary/fundamentals-of-software-defined-radio-and-cooperative-spectrum-sensing/46200

Automated Learning over Large Datasets and Time Horizons

The lack of large, common, open source datasets with extended time horizons is a significant barrier to developing and testing the AI algorithms necessary to automate spectrum management and sharing. Spectrum and network data are very time- and location-specific. Methods are needed for continual, distributed, and secure data collection and for data sharing that protects privacy. Possible approaches include leveraging the efforts at Federal research labs to make data available and using AI to augment small datasets (similar to how AI is used to generate synthetic datasets for self-driving cars[10]).

AI methods can improve existing spreadsheet-based spectrum allocation techniques and other manual processes. These systems could incorporate continual learning[11] that adapts quickly to changing field conditions and can assist in low-latency policy-making decisions. However, this would require the development and deployment of infrastructure that can test AI system performance in real time.

Role of AI Predictions in Spectrum Allocations

Successful AI techniques for management and assignment of spectrum allocations would be a game-changer. This is a rich research area, and regulatory agencies are experimenting with innovative spectrum access and management models (e.g., validating new AI spectrum allocation methods using measurements from experiments and synthetic datasets). Inferences made using AI techniques, when combined with long-term sensor data, can shorten the time frame for DSA decisions to minutes rather than days, and the reassignment of spectrum allocations based on actual use to years rather than decades.

To ensure the adoption and success of these AI techniques, stakeholders must be involved early in the process, and policies and technologies must evolve simultaneously. The following three actions are essential for success:

- ***Identify the problem to be solved.*** AI's ability to predict patterns is well accepted, and a hybrid solution involving both AI- and rule-based assignments could incorporate the best of each method.
- ***Test AI solutions*** on existing testbeds, and validate solutions prior to real-world use.
- ***Build trustworthy systems for users.*** Explainability and traceability are needed for acceptance, suitability, and improvement for AI/ML algorithms.

AI for Spectrum Sharing

Spectrum sharing has been the subject of intense research because of the ever-increasing demand for spectrum by new wireless applications and services. AI presents opportunities to mediate some of the challenging decision-making problems arising between independent users who want to share spectrum but avoid harmful interference. Whether for the users themselves (peer-to-peer sharing[12]) or for a control system (spectrum access system [SAS]) seeking to arbitrate between them, the available data is often incomplete, out-of-date, and noisy. An effective decision-making process depends on good data, but it must also account for the unpredictable actions of others and rapid changes in the environment. Because

[10] https://www.therobotreport.com/drive-ai-self-driving-simulation/

[11] Continual learning in AI is built on the idea of prediction models that learn continuously about the external world and enable the autonomous incremental development of ever more complex skills and knowledge.

[12] Peer-to-peer spectrum sharing is a decentralized form of spectrum sharing in which all participants have an equity stake in spectrum use.

of these complexities, AI decision systems have the potential to significantly outperform legacy designs and change the way spectrum is used. For example, the now-closed DARPA Spectrum Collaboration Competition (SC2)[13] sought to use AI to enable collaborative real-time automation of spectrum management without human intervention. SC2 explored collaboration on spectrum use, enabling radio networks to make decisions with greater certainty on shorter time scales through ML and other optimization techniques. SC2 scenarios considered the following topics as good choices for AI-based interventions: equitable division of resources, incumbent protection, pattern exploitation, convergence on new spectrum use solutions for changing demands, spatial reuse, and prioritization.

AI shows great potential, but moving it into the mainstream of spectrum-sharing practice will require additional R&D on many interconnected topics, including AI-enabled peer-to-peer spectrum sharing; AI-enabled SASs; and the validation, assurance, and certification of AI-enabled spectrum sharing.

AI-enabled Peer-to-Peer Spectrum Sharing

The challenges for AI in enabling peer-to-peer spectrum sharing range from highly theoretical issues to precise problems such as specific frequencies, wireless systems, incumbents, bands, and tasks (e.g., discrimination or control). Workshop participants discussed identifying the opportunity space, AI research and data, and establishing the value of data being shared between networks.

Opportunity space includes spectrum ecosystems where AI-enabled peer-to-peer sharing can be envisioned. In order to identify these ecosystems, the following criteria must be considered: the interaction of AI-based systems with non-AI systems; the future direction of peer-to-peer spectrum sharing (e.g., wireless systems, bands, and classes of technology); and metrics (e.g., spectrum utility, scalability of sharing across bands, and network sizes) to quantify the value of using AI to improve performance and other factors such as reliability.

Workshop participants discussed the following areas where AI-enabled peer-to-peer spectrum sharing could be feasibly deployed:[14] Wi-Fi 6/6 GHz,[15] DOD's Secure 5G program,[16] mmWave systems,[17] time-division duplexing,[18] and vehicle-to-vehicle[19] communications.

Research topics of interest in this space include using spectrum data for discrimination problems, data sufficiency and integrity, predictive AI, cross-domain AI decision making, service prioritization, waveform design, and detection of imperfections in networks. Two key research needs emerged from discussion of these topics:

[13] https://www.darpa.mil/program/spectrum-collaboration-challenge

[14] To simplify the process, workshop participants focused on spectrum bands that are allocated or repurposed for entirely new uses.

[15] Wi-Fi 6/6 GHz identifies devices that will offer the features and capabilities of Wi-Fi 6, including higher performance, lower latency, and faster data rates, extended into the 6 GHz band. https://docs.fcc.gov/public/attachments/DOC-363490A1.pdf

[16] https://www.defense.gov/Explore/News/Article/Article/1844423/dod-develops-secure-5g-mobile-telecommunication-network-strategy/

[17] E.g., https://www.nist.gov/programs-projects/millimeter-wave-communication-systems

[18] https://ieeexplore.ieee.org/document/8902468

[19] https://www.nhtsa.gov/technology-innovation/vehicle-vehicle-communication

- ***Distributed learning*** that understands the constraints in which distributed, heterogeneous, multiagent AI operates and learns; these AI agents could be on mobile devices, spectrum sensors, or other wireless devices.
- ***Heterogeneous sharing*** that ensures performance when sharing across different decision engines; research is needed on bounding AI to ensure convergent performance. Identifying the level at which AI should be applied is also required to enable system success on a peer-to-peer basis.

Certification, trust, and validation are major hurdles to enabling AI systems for peer-to-peer spectrum sharing. The data needed to apply AI techniques and validate the algorithms developed in various environments depend on the problem to be solved. In turn, the AI algorithm being used drives the data needed. For example, deep reinforcement learning requires archived data for training purposes.

Research is also needed to investigate the efficacy of sharing information between networks in a peer-to-peer context over the air and in-band. Potential research tasks include whether a network can quantify the value of sharing information, adopt network sharing to improve costs, and address the large economic disparities between networks.

AI-enabled SAS

The spectrum access system is a model-based, centralized system that automates spectrum management. The main takeaway from exploring key AI-enabled SAS applications is the need to identify the desired AI functions. The following SAS applications are candidates for incorporating AI:

- ***Propagation model augmentation*** that improves the precision of propagation models and the identification of relationships within large quantities of sensor data in local areas.
- ***Dynamic incumbent protection*** that redefines interference-protection boundaries by leveraging years of SAS data, interference reports, and sensors deployed in the field. Real-time deployment data could be used to train AI algorithms to dynamically define protection areas in close to real time.
- ***Enforcement and identification of bad actors*** to assist with the forensics process and help determine if problems are caused by malicious or accidental actions.
- ***Cybersecurity*** that infers activity in places that are not directly observable.

Validation, Assurance, and Certification of AI-enabled Spectrum Sharing

Trust is critical if AI-enabled, real-time, spectrum sharing environments are to be adopted. This will require research on reliable and trustworthy methods and techniques to verify, validate, and certify devices and systems. Workshop participants discussed the need for further research in the following key topics:

- ***Self-aware AI*** that recognizes when its operational inputs are outside the set it was trained on or outside the range it is certified to operate in, and that specializes in currently emerging explainable AI techniques for spectrum domains.
- ***Assurance at higher levels*** that provides overall system-level assurance by building in a top-level response such as a human-on-the-loop, or human-in-the loop[20] decision capability if AI-enabled components fail, misbehave, or must interact with multiple AI systems.
- ***Support tools*** that incorporate a system's obligations, metadata, operational conditions, reasoning ability (regarding what it can learn), and its collaborations with other agents, which in turn enable trust in the system's operations.

[20] The distinction between "human-in" and "human-on" the loop is based on whether humans make key decisions ("in the loop") or whether humans guide the overall system direction but leave specific actions to an AI system ("on the loop").

Conclusion

The Federal Government, through the *Executive Order on Maintaining American Leadership in Artificial Intelligence*,[21] *Executive Order on Securing the Information and Communications Technology and Services Supply Chain*,[22] and *National AI R&D Strategic Plan: 2019 Update*[23] demonstrates its support for research, development, and deployment of AI to drive innovation in areas of critical national interest, including U.S. wireless communications networks. The Federal interest in AI is also driven by the need to advance R&D in increasing spectrum efficiency, awareness, and flexibility, as noted in the NSTC report, *Research and Development Priorities for American Leadership in Wireless Communications*.[24]

This report reflects information gathered from a diverse set of scientific and engineering experts in AI, ML, networking, and spectrum management in three major areas: future communications networks, dynamic spectrum allocation and policy management, and spectrum sharing.

In addition to potential research themes, workshop participants also noted three key issues that need to be addressed:

- Thoroughly define the problem to be solved.
- Establish trust through validation using large-scale wireless testing regions to test potential AI solutions.
- Acquire the datasets that are needed to verify and validate algorithms developed in various environments.

The discussions at the August 2020 NITRD/WSRD AI & Wireless Spectrum workshop represent viewpoints from a single moment in time. The interplay between wireless spectrum and the evolution of AI and ML techniques (e.g., wireless systems for communications, radio navigation, radiolocation, meteorology, and remote sensing) will continue to introduce new opportunities and challenges for wireless spectrum policy and management. The specific methods for measuring and collecting data that will be needed to effectively implement ML techniques is an important research area. Collection, processing, and storage issues to support ML techniques may also be a challenge. Challenges notwithstanding, fueled by the ability to track, collect, and leverage enormous amounts of data, advances in AI show great promise for improving and automating the spectrum management systems that wireless communication networks depend upon.

The WSRD IWG will continue to explore these topics through active engagement, collaboration, and partnerships among industry, academia, and the Federal Government.

[21] https://www.whitehouse.gov/presidential-actions/executive-order-maintaining-american-leadership-artificial-intelligence/

[22] https://www.whitehouse.gov/presidential-actions/executive-order-securing-information-communications-technology-services-supply-chain/

[23] https://www.nitrd.gov/pubs/National-AI-RD-Strategy-2019.pdf

[24] https://www.nitrd.gov/pubs/Research-and-Development-Priorities-for-American-Leadership-in-Wireless-Communications-Report-May-2019.pdf

Abbreviations

5G	fifth-generation mobile networks
AI	artificial intelligence
DARPA	Defense Advanced Research Projects Agency
DSA	dynamic spectrum access
IT	information technology
IWG	interagency working group
ML	machine learning
NITRD	Networking and Information Technology Research and Development Program
NSF	National Science Foundation
NSTC	National Science and Technology Council
NTIA	National Telecommunications and Information Administration
O-RAN	Open Radio Access Network Alliance
R&D	research and development
SAS	spectrum access system
SC2	DARPA Spectrum Collaboration Competition
WSRD	Wireless Spectrum Research and Development (NITRD IWG)

About the Authors

The NITRD Program is the Nation's primary source of federally funded coordination of pioneering IT R&D in computing, networking, and software. The multiagency NITRD Program, guided by the NITRD Subcommittee of the NSTC Committee on Science and Technology Enterprise, seeks to provide the R&D foundations for ensuring continued U.S. technological leadership and meeting the Nation's needs for advanced IT. More information is available at https://www.nitrd.gov.

The WSRD IWG consists of Federal agency representatives who coordinate spectrum-related research and development activities both across the Federal Government and with the private sector and academia. The WSRD Co-Chairs are Thyaga Nandagopal, NSF, and Mike DiFrancisco, NTIA. More information is available at https://www.nitrd.gov/groups/wsrd.

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