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3 PREFACE

Knowledge Representation and Reasoning (KR) is a well-established and lively field of research. In KR, a fundamental assumption is that an agent's knowledge is explicitly represented in a declarative form, suitable for processing by dedicated reasoning engines. This assumption, that much of what an agent deals with is knowledge-based, is common in many modern intelligent systems. Consequently, KR has contributed to the theory and practice of various areas in AI, including automated planning and natural language understanding, and to fields beyond AI, including databases, verification, software engineering, and robotics. In recent years, KR has contributed also to new and emerging fields, including the semantic web, computational biology, cyber security, and the development of software agents.

The KR conference series is the leading forum for timely in-depth presentation of progress in the theory and principles underlying the representation and computational management of knowledge. It is intended to foster not only communication and a cross-fertilization of ideas within the area but also collaboration across research boundaries. As in previous KR conferences, the topics were diverse and covered a broad spectrum of research topics. Similar to last year's conference, in support of topic diversity and to showcase the role of KR in key areas, the following tracks and special sessions were included in addition to the main conference track:

- *Applications and Systems Track:* This track invited submissions of papers on emerging and deployed applications of KR, describing all aspects of the development, deployment, and evaluation of KR systems to solve real-world problems, including interesting case studies and benchmarks, and discussing lessons learned.
- *Recent Published Research Track:* This track provided a forum to discuss important results related to KR that appeared recently in selective journals and conferences, but have not been previously presented at KR.
- *Special Session on KR and Machine Learning:* This special session invited submissions of papers on synergistic integration of KR and machine learning methods.
- *Special Session on KR and Robotics:* This special session invited submissions of papers on synergistic integration of KR and Robotics methods.

We received 287 submissions to the main technical program (including the Applications and Systems track, and the Special Sessions on KR and Machine Learning, and KR and Robotics), of which 75 (26%) were accepted (60 full papers and 15 short papers). In addition, we received 17 submissions to the Recently Published Research Track, of which 12 were accepted for presentation at the conference.

This year the following papers received the best paper awards:

- *Ray Reiter Best Paper Award:* "Capturing Homomorphism-Closed Decidable Queries with Existential Rules", by Camille Bourgaux, David Carral, Markus Krötzsch, Sebastian Rudolph, and Michaël Thomazo.
- *Ray Reiter Best Paper Award Runner-Up:* "How to Approximate Ontology-Mediated Queries", by Anneke Haga, Carsten Lutz, Leif Sabellek, and Frank Wolter.
- *Marco Cadoli Best Student Paper Award:* "On the Progression of Belief", by Daxin Liu and Qihui Feng.
- *Marco Cadoli Best Student Paper Award Runner-Up:* "DEL-based Epistemic Planning for Human-Robot Collaboration: Theory and Implementation", by Thomas Bolander, Lasse Dissing, and Nicolai Herrmann.
- *Marco Cadoli Best Student Paper Award Runner-Up:* "Lifted Inference with Tree Axioms", by Timothy van Bremen and Ondřej Kuželka

Nominations for awards were made by area chairs and PC members, and the selection of award winners was the responsibility of this year's awards committee: Chitta Baral, Andreas Herzig, and Tommie Meyer. We thank them for contributing their time and expertise to this important task.

As with previous KR conferences, the conference program included invited talks by prominent researchers, spanning traditional KR&R topics, emerging applications, and connections to other research communities:

- Martin Grohe (RWTH Aachen University, Germany): *The Logic of Graph Neural Networks*
- Jochen Renz (Australian National University, Australia): *Spatial and Physical Reasoning: From Angry Birds to Open World AI*
- Uli Sattler (University of Manchester, United Kingdom): *Description Logic and OWL: A Tale of Discoveries, Design Choices, Challenges, and Lessons Learnt* (Great Moments in KR Talk)
- Josh Tenenbaum (MIT, United States): *Reverse Engineering Human Cognitive Development: What Do We Start With, and How Do We Learn The Rest?*
- Francesca Toni (Imperial College, United Kingdom): *The Interactionist View of Reasoning for Explainable AI*

Interspersed with the contributed and invited talks were the following sessions aimed at connecting members of our research community and discussing the future of the KR conference series:

- *Doctoral Consortium* (DC): In addition to a dedicated DC event, the Doctorial Consortium students delivered lightning talks during a plenary session of the main conference, followed by a poster session where they could discuss their work with other conference participants.
- *Diversity & Inclusion* (D&I): This year's conference included a session devoted to fostering diversity and inclusion in our research community, as well as further D&I-related activities.
- *Future of KR*: This session presented results of a survey about the format of future KR conferences and provided a forum for participants to share their views and ideas.

As in recent years, KR 2021 solicited workshop and tutorial proposals via an open call. We had a strong workshop

and tutorial program with a variety of interesting and timely topics covering the whole spectrum of KR:

- WS: *6th International Workshop on Semantics-Powered Health Data Analytics* (SEPDA)
- WS: *Explainable Logic-Based Knowledge Representation* (XLoKR)
- WS: *Ontology Uses and Contribution to Artificial Intelligence (OnUCAI)*
- WS: *Knowledge Representation for Hybrid and Compositional AI* (KRHCAI)
- WS: *2nd International Workshop on Second-Order Quantifier Elimination and Related Topics (SOQE)*
- WS: *1st International Workshop on Computational Machine Ethics* (CME)
- Tutorial: *Proof-Theoretic Approaches to Logical Argumentation*, Ofer Arieli and Christian Strasser
- Tutorial: *Completeness, Recall, and Negation in Open-World Knowledge Base*, Simon Razniewski, Hiba Arnaout, Shrestha Ghosh and Fabian M. Suchanek
- Tutorial: *Complex Event Recognition and Forecasting Elias*, Alevizos and Alexander Artikis
- Tutorial: *Planning with multi-agent, flexible, temporal, epistemic and contingent aspects* (MAFTEC), Aurélie Beynier, Frédéric Maris and Francois Schwarzentruber
- Tutorial: *Solving equations in modal and description logics*, Philippe Balbiani
- Tutorial: *KR&R Meets Cyber-Physical Systems: Formalization, Behavior, Trustworthiness*, Marcello Balduccini, Edward Griffor and Tran Cao Son
- Tutorial: *Belief Revision and Judgment Aggregation in Ontologies*, Jake Chandler and Richard Booth
- Tutorial: *Answer Set Programming: From Theory to Practice*, Roland Kaminski, Javier Romero, Torsten Schaub and Philipp Wanko

Additionally, KR 2021 was strengthened by the (virtual) co-location with the *20th International Workshop on Non-Monotonic Reasoning* (NMR 2021).

The planning and organization of KR 2021 took place in the context of the ongoing Covid-19 pandemic. While initially we planned for a hybrid event with a physical component in Hanoi, Vietnam, it became evident over time that travel to Vietnam would most likely be difficult, if not impossible, for many members of our research community. The decision was therefore taken to switch to a fully virtual format, and the dates of the conference were extended to November 3-12 in order to add an extra day for the main conference and to allow the workshops, tutorials, and the Doctoral Consortium to be held during the work week. To maximize interactions, every accepted contribution to the technical program was allocated both an oral presentation (delivered live in Zoom) and a poster presentation (with poster sessions organized in a Gather space). The conference schedule was carefully crafted to accommodate the timezone constraints of the authors and to allow participants from all corners of the globe to attend at least some parts of the program live. In addition, recordings of all oral presentations were made available to the participants, and Slack channels were set up to enable asynchronous discussions. Finally, due to improving conditions in Europe, it was decided to organize a live KR gathering at La Sapienza University in Rome, Italy, so that part of the KR community could meet in person and watch the technical program together.

We wish to thank everyone who contributed to the success of KR 2021. First, let us start by thanking our Track and Special Session Chairs for their very capable management of their respective tracks and sessions: Martin Gebser and Ulrike Sattler (Applications & Systems Track), Vladimir Lifschitz and Pierre Marquis (Recently Published Research Track), Vaishak Belle and Luc de Raedt (Special Session: KR & Machine Learning), Alessandro Saffioti and Mary-Anne Williams (Special Session: KR & Robotics). We also thank this year's Area Chairs for the integral role they played in the review and selection process, as well as our Program Committee members and additional reviewers for their thorough and timely reviews of the submissions. Next, let us acknowledge the important efforts of Markus Krötzsch and Yongmei Liu in selecting and coordinating the Workshop and Tutorial program, of Jens Claßen and Magdalena Ortiz in organizing this year's Doctoral Consortium, and of Marco Maratea, Maria Vanina Martinez, and Magdalena Ortiz in putting together the Diversity & Inclusion session and activities. Even with the switch to a purely online format, our local chairs were kept busy with many organizational tasks, so a big thanks to Thanh Van Dinh, Tran Cao Son, Long Tran-Thanh, and Giuseppe De Giacomo (an extra thanks to Giuseppe for organizing the live gathering in Rome). We also acknowledge the successful efforts of Kuldeep S. Meel and Zeynep G. Saribatur in finding sponsors, and we thank our publicity chairs, Thanh Van Dinh and Paolo Felli, for handling mailing list distributions and the creation and maintenance of the KR'21 webpage, respectively. We are also incredibly grateful to our virtual conference arrangements committee – Stefan Borgwardt, Marco Console, and Long Tran-Thanh – who took charge of all aspects related to the online platforms and online activities (with some extra help and advice from Paolo Felli, who handled last year's virtual arrangements).

In closing, we would like to thank all of our colleagues who contributed to the continued success of the KR conference series through their active participation in KR 2021.

Meghyn Bienvenu and Gerhard Lakemeyer
Program Chairs

Esra Erdem
General Chair

4 INVITED TALKS

The Logic of Graph Neural Networks

Martin Grohe, Aachen University, Germany

Graph neural networks (GNNs) are a deep learning architecture for graph structured data that has developed into a method of choice for many graph learning problems in recent years. It is therefore important that we understand their power. One aspect of this is the expressiveness: which functions on graphs can be expressed by a GNN model? Surprisingly, this question has a precise answer in terms of logic and a combinatorial algorithm known as the Weisfeiler Leman algorithm.

My talk will be a survey of recent results linking the expressiveness of GNNs to logical expressivity.

Martin Grohe is a Professor for Theoretical Computer Science at RWTH Aachen University. He received his Ph.D. in Mathematics at Freiburg University in 1994 and then spent a year as a visiting scholar at Stanford and the University of California at Santa Cruz. Before joining the Department of Computer Science of RWTH Aachen in 2012, he held positions at the University of Illinois at Chicago, the University of Edinburgh, and the Humboldt University at Berlin.

His research interests are in theoretical computer science interpreted broadly, including logic, algorithms and complexity, graph theory, theoretical aspects of machine learning, and database theory.

Spatial and Physical Reasoning: From Angry Birds to Open World AI

Jochen Renz, Australian National University, Australia

Research on "naïve physics", qualitative reasoning, spatial and temporal reasoning has been an important part of KR for over 40 years. The distinctive feature of this type of reasoning is that the domains over which we are reasoning are typically infinite and continuous. This feature is of high practical importance as it is omnipresent when interacting with the real physical world. Future AI agents need these reasoning capabilities to perform their tasks in the physical world safely and reliably, just like humans. These agents will mostly have only partial information about their environment, for example, through noisy perception. Their action space will be continuous, and the exact outcome of their physical actions might be unknown in advance, which makes it very difficult to determine action sequences that solve a given physical task. In addition, the presence of entities in the environment with unknown properties will make these physical tasks even harder. To promote research in this important area, and to enable the required agent capabilities, we have established the Angry Birds AI Competition which covers the major challenges of interacting with the physical world in a simplified and controlled environment. After nine annual competitions, KR-based approaches vastly outperform learning-based approaches. In this talk, I will present and motivate this area, summarise different approaches, future challenges, and how KR research can be integrated with other subfields of AI to make a real impact in this area.

Jochen Renz is a Professor for Artificial Intelligence at the Australian National University. He did his PhD at the University of Freiburg in 2000, followed by a postdoc at the University of Linkoping, and a Marie-Curie Fellowship at TU Vienna. In 2003 he moved to the National ICT Australia in Sydney and in 2006 to the Australian National University in Canberra where he was promoted to full professor in 2013. Jochen published his first KR paper in 1998 on theoretical foundations of spatial reasoning. In 2012, he organised the first Angry Birds AI Competition, which is now held annually as part of IJCAI. Jochen's research has been focusing on theoretical and practical aspects of spatial and physical reasoning and on integrating it with other AI areas to solve challenging problems.

Description Logic and OWL: A Tale of Discoveries, Design Choices, Challenges, and Lessons Learnt

(Great Moments in KR Talk)

Uli Sattler, University of Manchester, United Kingdom

Description Logic and ontology languages, in particular OWL, have now been around for a long time, with an active research community developing a plethora of KR formalisms, reasoning tasks, algorithms, reasoners, and computational complexity results. The relationships with other formalisms are well-understood and a rich infrastructure has been developed. In this talk, I will discuss some of the advances, discoveries, and design choices that were made on this journey as well as some of the challenges faced and insights gained, with a focus on the use of Description Logic as the underpinning of OWL and the ensuing demands. The talk should be accessible to the broad KR community and give the audience a better understanding of DLs and OWL, and current developments.

Uli Sattler is a professor at the University of Manchester, working in logic-based knowledge representation, Description Logics, and ontology engineering. Together with colleagues, she designed the family of Description Logics underpinning ontology languages such as OWL and decision procedures for relevant reasoning problems of these logics. She has been working on a range of novel reasoning problems that are important for ontology engineering and United Statesge such as module extraction and decomposition, entailment explanation, and mining axioms from data. Uli completed her PhD under the supervision of Franz Baader at RWTH Aachen and her habilitation at TU Dresden.

Reverse Engineering Human Cognitive Development: What Do We Start With, and How Do We Learn The Rest?

Josh Tenenbaum, MIT, United States

What would it take to build a machine that grows into intelligence the way a person does — that starts like a baby, and learns like a child!? AI researchers have long debated the relative value of building systems with strongly prespecified knowledge representations versus learning representations from scratch, driven by data. However, in cognitive science, it is now widely accepted that the analogous

"nature versus nurture?" question is a false choice: explaining the origins of human intelligence will most likely require both powerful learning mechanisms and a powerful foundation of built-in representational structure and inductive biases. I will talk about our efforts to build models of the starting state of the infant mind, as well as the learning algorithms that grow knowledge through early childhood and beyond. These models are expressed as probabilistic programs, defined on top of simulation engines that capture the basic dynamics of objects and agents interacting in space and time. Learning algorithms draw on techniques from program synthesis and probabilistic program induction. I will show how these models are beginning to capture core aspects of human cognition and cognitive development, in terms that can be useful for building more human like AI. I will also talk about some of the major outstanding challenges facing these and other models of human learning.

Josh Tenenbaum is Professor of Computational Cognitive Science at MIT in the Department of Brain and Cognitive Sciences, the Computer Science and Artificial Intelligence Laboratory (CSAIL) and the Center for Brains, Minds and Machines (CBMM). He received his PhD from MIT in 1999, and taught at Stanford from 1999 to 2002. His long-term goal is to reverse-engineer intelligence in the human mind and brain, and use these insights to engineer more human-like machine intelligence. His current research focuses on the development of common sense in children and machines, the neural basis of common sense, and models of learning as Bayesian program synthesis. His work has been published in Science, Nature, PNAS, and many other leading journals, and recognized with awards at conferences in Cognitive Science, Computer Vision, Neural Information Processing Systems, Reinforcement Learning and Decision Making, and Robotics. He is the recipient of the Distinguished Scientific Award for Early Career Contributions in Psychology from the American Psychological Association (2008), the Troland Research Award from the National Academy of Sciences (2011), the Howard Crosby Warren Medal from the Society of Experimental Psychologists (2016), the R&D Magazine Innovator of the Year award (2018), and a MacArthur Fellowship (2019). He is a fellow of the Cognitive Science Society, the Society for Experimental Psychologists, and a member of the American Academy of Arts and Sciences.

The Interactionist View of Reasoning for Explainable AI

Francesca Toni, Imperial College London, United Kingdom

The interactionist view to human reasoning states that "the normal conditions for the use of reasons are social and more specifically dialogic" and that "people use reasons as arguments in favor of new decisions or new beliefs" [1]. In this talk I will explore how this view can be naturally transferred onto machine reasoning to support the vision of explainable AI (XAI) as computational argumentation. I will briefly overview the field of XAI, which, while having been investigated for decades, has witnessed unprecedented growth in recent years, alongside AI itself. I will then show that computational argumentation can be used to provide a variety of explanations, including dialogic ones, for the outputs of a variety of AI methods, leveraging on computational argumentation's wide array of reasoning abstractions. In particular, following [2], I will overview the literature focusing on different types of explanation (intrinsic and post-hoc, which in turn may be approximate or complete), different forms of AI with which argumentation-based explanations are deployed, different forms of delivery of explanations (including, prominently, dialogic ones), and different argumentation frameworks they use from within the several proposed in computational argumentation. I will conclude by laying out a roadmap for future work within this exciting area.

[1] Mercier and Sperber: The Enigma of Reason - a New Theory of Human Understanding. Harvard University Press 2017

[2] Cyras, Rago, Albini, Baroni, Toni: Argumentative XAI: A Survey. IJCAI 2021.

Francesca Toni is Professor in Computational Logic and Royal Academy of Engineering/JP Morgan Research Chair on Argumentation-based Interactive Explainable AI at the Department of Computing, Imperial College London, United Kingdom, and the founder and leader of the CLArg (Computational Logic and Argumentation) research group. Her research interests lie within the broad area of Knowledge Representation and Reasoning in AI and Explainable AI, and in particular include Argumentation, Argument Mining, Logic-Based Multi-Agent Systems, Non-monotonic/Default/Defeasible Reasoning, Machine Learning. She graduated in Computing at the University of Pisa, Italy, and received her PhD in Computing from Imperial College London. She has coordinated two EU projects, received funding from EPSRC in the United Kingdom and the EU, and was previously awarded a Senior Research Fellowship from The Royal Academy of Engineering and the Leverhulme Trust. She is currently Technical Director of the ROAD2H EPSRC-funded project (www.road2h.org/) and co-Director for the United KingdomRI Centre of Doctoral Training in AI for Healthcare (https://ai4health.io), and was founding co-director of the United KingdomRI the Centre of Doctoral Training in Safe and Trusted AI (https://safeandtrustedai.org). Also, she has recently been awarded an ERC Advanced grant on Argumentation-based Deep Interactive eXplanations (ADIX). She has published over 200 papers, is EurAI fellow, has co-chaired ICLP2015 (the 31st International Conference on Logic Programming) and KR 2018 (the 16th Conference on Principles of Knowledge Representation and Reasoning), is the current chair for COMMA 2022 (the 10th International Conference on Computational Models of Argument), corner editor on Argumentation for the Journal of Logic and Computation, in the editorial board of the Argument and Computation journal and the AI journal, and in the Board of Advisors for KR Inc. and Theory and Practice of Logic Programming.

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