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21st International Semantic Web Conference
Virtual Event, October 23–27, 2022
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Editors
Ulrike Sattler
University of Manchester
Manchester, UK

Maria Keet
University of Cape Town
Cape Town, South Africa

João Paulo A. Almeida
Universidade Federal do Espírito Santo
Vitória, Brazil

Pierre Monnin
Orange
Belfort, France

Claudia d'Amato
University of Bari
Bari, Italy

Aidan Hogan
University of Chile
Santiago, Chile

Valentina Presutti
University of Bologna
Bologna, Italy

Hideaki Takeda
National Institute of Informatics
Tokyo, Japan

Giuseppe Pirrò
Sapienza University of Rome
Rome, Italy

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Preface

The International Semantic Web Conference (ISWC) has established itself down through the years as the premier international forum for the Semantic Web and Knowledge Graph community, discussing and presenting the latest advances in fundamental research, innovative technology, and applications concerning semantics, data, and the Web. ISWC brings together researchers, practitioners, and industry specialists to discuss, advance, and shape the future of semantic technologies.

It is my honor to introduce the proceedings of ISWC 2022 and to be the general chair for the 21st edition of this conference. It has also been a rewarding experience working with the team of chairs and organizers that all together played a key role in driving the conference and leading it to success. My gratitude and acknowledgment also go to the Senior Program Committee (SPC), to the 475 Program Committee (PC) members, and the 66 additional reviewers who produced over 1,139 peer reviews, thus making it possible for ISWC 2022 to keep the excellent reputation as a premier scientific conference.

The original plan for ISWC 2022 was to run it as a hybrid event in Hangzhou, China, thus providing the research community the opportunity to meet in person again (after two virtual conference editions), while taking into account possible COVID-19 restrictions, traveling issues due to limited funds, visa problems, and so forth. Unfortunately, due to the increasing COVID-19 restrictions in China, which also prevented travel within China, we had to switch ISWC 2022 to a fully virtual event.

The conference runs for five days, offering a rich program spanning different tracks (Research, Resources, In-Use, and Industry Tracks), Workshops and Tutorials, Posters, Demos, and Lightning Talks, a Doctoral Consortium, Challenges, and Panels. In collaboration with the Semantic Web Science Association (SWSA), this year we also agreed on a new policy regarding submissions with plagiarized content: authors of such submissions will be banned from submitting to ISWC for two years.

ISWC 2022 received 335 submissions, authored by 1,363 distinct authors from 35 different countries, with China, Germany, the USA, France, and Italy featuring prominently in the submissions list. The final program was the result of a very rigorous and constructive review process, supported also by detailed guidelines for reviewers that were set up and made publicly available for this conference edition. The review process for papers submitted to the Research, Resources, and In-Use Tracks also encompassed the new Objection and Response phase (that replaced the Rebuttal phase usually adopted), aiming at reducing workload on authors and reviewers, while providing an opportunity for author feedback in two exceptional cases: a) highlighting clear factual errors in reviews regarding the content of the submission and b) responding to explicit questions from reviewers. ISWC 2022 further emphasized reproducibility, being a key aspect of scientific research. For this purpose a detailed policy for supplemental materials and reproducibility was made publicly available. It required authors to add a statement, at

the end of the submission, covering all of the resources necessary to reproduce or verify the results presented in the paper. These resources may include datasets, queries, code, proofs of results, configuration details, hyperparameters, etc., depending on the contributions of the paper. The statement is aimed at facilitating the independent reproducibility or verification of the results presented, pointing to where supplemental material can be found. Reviewers were asked to evaluate the statement in terms of its ability to ensure reproducibility of the paper results as well as availability (also for the foreseeable future) of resources. Additionally, to facilitate reproducibility and give peer reviewers a characterization of a submission by juxtaposing it with related approaches, authors were encouraged to optionally accompany their submission with a comparison in the Open Research Knowledge Graph (ORKG)[1].

These proceedings collect together accepted papers from the ISWC 2022 Research, Resources, and In-Use Tracks, while accepted papers in the Industry Track, Poster and Demos Track, Doctoral Consortium, and the various accepted workshops and Semantic Web challenges have been published as CEUR Workshop Proceedings[2].

The Research Track this year was chaired by Aidan Hogan and Uli Sattler. The track solicits submissions on novel research contributions that further advance the Semantic Web, and received a total of 156 full paper submissions. As in previous years, we received submissions with a range of contributions which can be classified in the following four categories. Firstly, papers on classic reasoning and query answering over ontologies of various shapes (e.g., RDF(S)/OWL, SHACL, SPARQL, and variations or extensions of these), as well as non-standard tasks like repair, explanation, and database mappings. Following the trend of past years, we also received a number of papers on embeddings of ontologies/knowledge graphs, in particular various forms of graph neural networks, and their usage in a range of applications, including zero/few shot learning, image/object classification, and various NLP tasks. Another category of papers focuses on specific knowledge graph tasks like link or type prediction and entity alignment. Finally, we received a small number of surveys of the state of affairs, e.g. on LOD availability and structural patterns in ontologies. Instrumental to shaping the final program were the 214 Program Committee members who provided reviews, and the 27 Senior Program Committee members who helped oversee the reviewing process and drafted meta-reviews. A total of 46 external reviewers, solicited by PC members, contributed valuable additional reviews to the process. Following the precedent of previous editions of ISWC, the Research Track was double blind. All papers received three to four reviews. Ultimately, 30/156 papers were accepted, giving an acceptance rate of 19.2%, which is comparable with recent years of the ISWC Research Track.

The Resources Track, chaired by Maria Keet and Valentina Presutti, promoted the sharing of resources that support, enable, or utilize Semantic Web research, and in particular datasets, ontologies, software, and benchmarks. This track received 60 papers for review. Each paper was subject to a rigorous single-blind review process involving at least three reviewers, and on average four, and discussions among reviewers as well as

[1] https://orkg.org/.
[2] http://ceur-ws.org/.

an Objections and Response phase. The main review criteria focus on impact (novelty of the resource), reusability, the design and technical quality, and availability. Eventually, 11 papers were accepted. The Resources Track was aided by seven SPC and 54 PC members, and nine additional reviewers.

The In-Use Track this year was chaired by João Paulo A. Almeida and Hideaki Takeda. This track provides a forum to explore the benefits and challenges of applying Semantic Web and Knowledge Graph technologies in concrete, practical use cases, in contexts ranging from industry to government and society. In total, seven full papers were accepted for the In-Use Track, selected out of 23 full papers sent for peer review (30.43% acceptance rate). All submissions were thoroughly reviewed in a single-blind process by three Program Committee members. Submissions were assessed in terms of novelty (of the proposed use case or solution), uptake by the target user group, and demonstrated or potential impact, as well as overall soundness and quality. An Objection and Response phase was also implemented this year in line with the other tracks of the conference. Overall, 41 PC members and two additional reviewers participated in a rigorous review process.

These proceedings also include abstracts of the talks given by three excellent keynote speakers, Markus Krötzsch, Francesca Rossi, and Ilaria Capua, that ISWC 2022 was delighted to host. Markus Krötzsch, prominent member of the Semantic Web and Knowledge Graph community, gave the talk on "Data, Ontologies, Rules, and the Return of the Blank Node", presenting his view on how the unification of data and ontology may present an opportunity to the Semantic Web, and how recent results in rule-based reasoning may provide a basis for overcoming related challenges. Francesca Rossi, leading academic and industrial researcher in Artificial Intelligence (AI), gave the talk titled "AI Ethics in the Semantic Web", presenting the main issues around AI ethics, some of the proposed solutions, and the relevance of some AI ethics issues to the Semantic Web. Ilaria Capua, virologist widely recognized internationally and pioneering genetic data sharing to improve pandemic preparedness, gave the talk on "Circular Health", presenting her view of health as a circular model and illustrating how this circular approach could be data driven and implemented by using the Sustainable Development Goals roadmap.

The Industry Track, this year chaired by Anna Lisa Gentile and Petar Ristoski, covers all aspects of innovative commercial or industrial-strength Semantic Technologies and Knowledge Graphs in order to showcase the state of adoption. This track received 15 papers for review, of which eight were accepted (53.3% acceptance rate) following a single-blind review process. The 18 members of the Program Committee assessed each submission in terms of qualitative and quantitative business value, as well as the innovative aspects, impact, and lessons learned of applying Knowledge Graph and Semantic Technologies in the application domain.

The Workshop and Tutorial Track was chaired by Marta Sabou and Raghava Mutharaju. In total, 11 workshops were part of the conference program covering research topics related to ontology engineering (ontology design patterns and ontology matching), data management topics (data evolution and preservation as well as storing, querying, and managing data at Web scale), interaction with users and synergies with other

technology fields, in particular deep learning. A number of workshops also focused on applications of Semantic Web technologies such as Wikidata, knowledge graph summarization, linked open science, managing legal documents and managing musical heritage with knowledge graphs. Three workshops (on legal document management, knowledge graphs summarization and musical heritage knowledge graphs) were offered for the first time, bringing new topics in addition to the topics investigated by the other established workshops. Six tutorials offered conference attendees the opportunity to further expand their knowledge on core technical topics such as reasoning, schema discovery, and knowledge-aware zero-shot learning or on topics related to exciting application domains such as autonomous driving and managing earth observation data.

The Semantic Web Challenges Track, chaired by Catia Pesquita and Daniele Dell'Aglio, proposed five challenges to help create and consolidate communities that foster research by developing solutions. Each challenge offered common environments to compare and contrast systems in various settings and tasks. The topics covered include federated query answering, neuro-symbolic reasoning, question answering, knowledge graph construction from language models, and tabular data to knowledge graph matching. Three challenges were re-editions of events proposed in the past (Semantic Answer Type, Entity, and Relation Linking Task; Semantic Reasoning Evaluation Challenge; and Semantic Web Challenge on Tabular Data to Knowledge Graph Matching) continuing their activity of driving and consolidating research trends within the Semantic Web. Two new challenges (Bio2RDF and Kibio federated query in Life Science Challenge and Knowledge Base Construction from Pre-trained Language Models) were introduced as part of the program, with a high potential to follow the successful path of the others and get a stable presence in future ISWC editions.

The Posters, Demos and Lightning Talks Track was chaired by Anastasia Dimou and Armin Haller. This track complements the paper tracks of the conference by offering an opportunity to present late-breaking research results, on-going projects, and speculative or innovative work in progress. Specifically, the Posters, Demos and Lightning Talks Track encourages presenters and participants to submit papers which have the potential to spark discussions about the work, forming an input for the future work of the presenters while offering participants an effective way to broaden their knowledge of emerging research trends and to network with other researchers. This track received 52 papers for review, of which 26 were accepted (50% acceptance rate). Among the accepted papers, 12 were poster papers and 14 were demo papers. The 55 members of the Program Committee were involved in a single-blind review process and assessed each submission based on relevance to the Semantic Web, originality, potential significance, topicality, and clarity.

Another important tradition of ISWC is the Doctoral Consortium (DC) which gives PhD students the opportunity to present their research ideas and initial results and to receive constructive feedback from senior members of the community. This year's DC was chaired by Oshani Seneviratne and Olaf Hartig, and received 10 submissions. Each submission was reviewed by four members of a Program Committee that consisted of 22 members in total. Based on the reviews, that were managed in agreement with a single-blind review process, six submissions were accepted to be published in the DC proceedings and the students of these submissions were invited to present their ideas

and work during the DC sessions of the conference, where they received further feedback from senior conference attendees. The DC also hosted a career-advising session, consisting of senior researchers providing career advice with an open Q&A session.

The conference program also included two panel discussions with invited panelists from industry and academia. The first panel was led and moderated by Pascal Hitzler. It was on the topic "Is the deep learning hype good or bad for the Semantic Web?", following the observation that deep learning methods are currently having significant impact on Semantic Web research, perhaps sometimes even leading to a neglect of important topics because they cannot be tackled readily with deep learning approaches. The second panel was led and moderated by Steffen Staab. This panel asked academic and industrial researchers the question "Knowledge Graphs for The Physical World—What is Missing?". Indeed, applications like smart homes, autonomous driving, robotics, or digital twins may benefit from explicit knowledge about the physical world and for this purpose must integrate a wealth of data sources; however, the academic progress appears to be slow, while existing standards seem not to fully meet industry needs.

Any conference cannot be run properly without the precious support of sponsors. As such I would like to express my gratitude to Matteo Palmonari, Guilin Qi, and Francois Scharffe for the great efforts they made to engage sponsors and promote the conference. At the same time my thanks go to all sponsors (listed below and on the conference website) that believed in ISWC 2022 and gave it very important financial support that allowed also the provision of grants to students and researchers who could not have otherwise registered for the conference. In this regard I would also like to mention ORKG which contributed with some additional student grants. A special thank goes to the Diamond and Platinum sponsors, and to Springer for additionally supporting the conference awards.

I would like to thank Pierre Monnin and Giuseppe Pirrò for their very diligent work in setting up the ISWC 2022 proceedings and also for making possible the capturing and publicly sharing of the conference data in a reusable and open format.

ISWC 2022 news and updates have been constantly spread within the Semantic Web and Knowledge Graph community and beyond. This has been possible thanks to the incessant commitment of Neha Keshan, publicity and job fair chair, and Wen Zhang, Web presence chair.

The uncertainty that ISWC 2022 had to face and that successive change of the conference format impacted particularly the local organization team that nevertheless worked diligently to ensure the best conference setting. I am grateful to the local chair, Huajun Chen, and to Wen Zhang and the rest of the team for the careful management of all conference activities.

Finally, my special thanks go once more to the whole organizing committee, that is the family of all chairs that shared with me this complicated but wonderful journey to finally delivering the ISWC 2022 conference, and to the Semantic Web Science Association (SWSA) for the valuable support to this year's conference and for the constant and continuous presence in ISWC's 21 year history.

Claudia d'Amato, ISWC 2022 General Chair, on behalf of all the editors.

September 2022

Ulrike Sattler
Aidan Hogan
Maria Keet
Valentina Presutti
João Paulo A. Almeida
Hideaki Takeda
Pierre Monnin
Giuseppe Pirrò
Claudia d'Amato

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Abstracts of Invited Talks

Circular Health

Ilaria Capua

One Health Center of Excellence, University of Florida,
Gainesville, Florida, USA
icapua@ufl.edu

Pandemics are unique and transformational events as they shake lives by exposing the vulnerability of Homo sapiens to previously unknown pathogens, which become widespread as most human beings on the planet will become infected. But Covid-19 has done much more than this. It has exposed us to another type of vulnerability – the **vulnerability of the systems we operate in**. It has also opened our eyes to the harsh reality that we live in a closed system, in which we are entirely **interconnected and interdependent with other creatures on planet earth**. This awareness has paved the way to acknowledge that as a society we should embrace the One Health [1] approach which recognizes the links between the health of humans, animals, and the environment.

Covid 19 has also shown us that such a major health crisis has multiple drivers and ramifications that include social [2], economic [3], and digital [4] drivers that have caused the pandemic to unravel in the way it did. In addition Covid 19 is the **most measured event** in history and oceans of big data have been generated during this event.

Since the turn of the millennium we have been experiencing several other challenges which concern our closed system and affect our health, for instance the climate [5] and food [6] crises. For example, we are aware of the devastating effect of rising temperatures on the health of our oceans, on the loss of biodiversity and on the migration of humans and animals. We are also well aware that the planet's demographics will require more food to feed a world population expected to reach 9.7bn by 2050 [7] and at the same time we have committed to diminishing greenhouse gas emissions to reduce pollution and CO2 footprint.

Following the conceptual blueprint of Circular Economy [8] and Circular Agriculture [9], this could be the right time to expand our approach to health to a circular model which encompasses the intricate and novel links between human health and the health of this closed system. This circular approach would be data driven and could be implemented by using the Sustainable Development Goals (SDGs) roadmap as an accelerator of convergence for health. All the 17 goals have ties to the health of humans, animals, plants, and the environment, and it would seem reasonable to prioritize certain activities and capitalize on existing guidelines and commitments.

The novelty of the Circular Health approach is to use post-Covid-19 renewed health priorities to promote the convergence of health-related issues which can be achieved within the Sustainable Development Goals framework. In this way it will be possible to advance urgent health priorities within an existing framework which aims at sustainability and at advancing health as an essential resource within a closed system, which needs to be regenerated and addressed in its complexity.

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Data, Ontologies, Rules, and the Return of the Blank Node

Markus Krötzsch

Knowledge-Based Systems Group, TU Dresden, Germany
markus.kroetzsch@tu-dresden.de

Abstract. The Semantic Web has long been characterised by the parallel development of machine-readable data and ontological models. Inspired by very different backgrounds – Web data exchange and mathematical logic – the two worlds have sometimes be perceived as complementary, even conflicting. But the general trend towards knowledge graphs made such discussions irrelevant, and modern knowledge models, such as Wikidata, often combine instance and schema data side by side. In my invited talk, I will explain how this unification of data and ontology may present an opportunity to the Semantic Web, and discuss how recent results in rule-based reasoning may provide a basis for overcoming related challenges. This involves some interesting insights about the expressive power that is conferred by extending rules with value invention – the ability to create fresh blank nodes. Besides the theoretical effects of this addition, we can also demonstrate concrete practical uses of this expressive power.

Ontologies have come a long way. In the past two decades of Semantic Web research, the community has re-invented itself several times. The first golden era of "ontology" saw the heydays of upper-level ontologies, design methodologies, and the birth and rise of the first OWL standard. Remarkable accomplishments of engineering and applied logic kept pushing what was possible. Meanwhile, "data" prepared for its comeback, with Linked Data, the first DBpedia releases, and of course SPARQL drawing our attention and resonating with the newly discovered appeal of *Big Data* (a marketing term both decried and revered by the data management community). New hybrids of data and ontology emerged, from *ontology-based data access* to the renewed data-centred modeling approaches of RDF constraint languages (eventually resulting in the unequal siblings ShaCL and ShEx). The new era of *knowledge graphs* finally saw the breakthrough of Semantic Web concepts: Google turned from mere document retrieval to question answering, the majority of Web pages now carry machine-readable annotations in shared vocabularies, and tens of thousands of Wikipedia editors construct a structured world model in Wikidata.

And where did this leave ontology? Considering today's large knowledge graphs with little or no OWL usage, we might wonder whether we lost it along the way. Indeed, this would seem to fit the zeitgeist. With the celebrated successes of machine learning, it seems that end-to-end AI has replaced our once-treasured *shared Conceptualization.* Only a short-sighted observer, however, could mistake this for a sign that (linked) data

has finally triumphed over (formal) ontology. Unfazed by the animosities of the past, we see that any such AI-induced *end of ontology* would also be the *end of semantic data*: in a world where any string of symbols is "machine-readable", the Semantic Web endeavour looses its meaning and relevance. Fortunately, such worries are unfounded, as data-driven AI longs for meaning and seeks (but so far fails to find) a method for *explaining* itself – for establishing a shared understanding with its human users.

Did we then falsely abandon ontology in favour of mere data? I do not think so. Instead, what we see in practice rather seems to be a marriage of data and ontology. Syntactically, this is no news to us, with OWL relying on an RDF syntax from its very beginnings. However, conceptually, we have often drawn clear boundaries between ontology (*schema*) and data (*instances*), where the former must adhere to strict formal standards and total consistency, while the latter is entitled to noise and incoherence. In modern knowledge graphs, such as Wikidata, both worlds are one [14]. Indeed, when we see a Wikidata statement like "elephant – has part(s) – elephant's trunk" it is hard not to read this "triple" as a mereological description of all instances of the class elephant. At the same time, such statements can be subject to all the complications associated with other data, from noise to context-dependent validity.

We are not well prepared for this messy new world. Where we used to have W3C-standardised ontology languages and specialised tools to deal with them, we now have noisy fusions of schema and instance data, sometimes with new user-invented expressive features that further blur the line between data and ontology (as in the Wikidata statement "universe – has part(s) of the class – astronomical object"). In the wild, we therefore find makeshift queries and ad-hoc tools where our Semantic Web forebears had planned for a neatly constructed layer cake. The challenge for staying relevant therefore is to combine the flexibility and robustness of custom scripts with the declarativity and reliability of an ontological reasoner.

One possible answer to this call is to turn to *rules*. Statements with an "if-then" structure have a natural place in both computation and logic, and many species of rule languages can be found within this fertile middle ground. The simplest (in syntax and semantics) is *Datalog* [1], where rules merely "materialise" query results by adding inferred relations between existing objects. Recursion adds power to this simple idea. It is easy to see the appeal of this approach: rules are simple "instructions" for data completion and transformation; they are fully declarative (implementation-independent); they are well-suited for handling complex relationships in knowledge graphs.

And rules can capture ontologies. This was known for a long time for some ontologies that could directly be rewritten as rules, most prominently the OWL RL profile [13]. The original idea was to turn ontologies into sets of rules, rather than allowing us to interpret part of the data as ontological information, which is then processed by rules. However, we can also define a set of (Datalog) rules that "implements" a complete OWL RL reasoner for input ontologies given as plain data (e.g., as RDF encoding of the OWL statements). A similar feat can be accomplished for the OWL EL profile although this ontology language cannot be rewritten in Datalog [10]. These approaches show that rules have the potential of capturing ontological semantics while at the same time being user-definable and therefore able to adapt to new forms and features in ways that a classical OWL reasoner could not.

However, this approach soon meets its limits, as can be seen by applying a small amount of complexity theory. Datalog can be evaluated in polynomial time with respect to the size of the input data, so if the input data is our ontological knowledge, we can only solve polynomial ontology reasoning tasks. But beyond lightweight profiles like RL and EL, ontological reasoning is not known for its low computational complexity: OWL 2 DL makes it to a frightening N2ExpTime-completeness. It might seem that rules, after all, can only do simple manipulations but are no use for such heavy lifting.

This is indeed true for Datalog, but it turns out that small extensions suffice to overcome all limits and capture a much larger class of computations. All we need to do is to allow rules to infer the existence of new objects. This so-called *value invention* leads us to *existential rules*. As recently discovered, even the known (and implemented) decidable fragments of this language are powerful enough to express *every* decidable computation that only relies on positive information (since we have no negation here) [2]. A huge leap from Datalog's polynomial time.

Interestingly, the "invented values" that are at the heart of this leap in expressive power are, in Semantic Web terms, nothing but *blank nodes* – the least appreciated type of RDF term, which has long been "considered harmful" in data publishing. This critique in publishing still holds up, but at the same time, blank nodes reveal their virtues when modelling computation. Indeed, the ability to build new structures from such elements is an important ingredient to the expressive power of existential rules. The other important ingredient, as it turns out, is the ability to re-use such blank nodes once they were created. It is this facility that allows even highly complicated computations to come to an end, instead of creating new values forever. The interplay between recursive rule application and the possible re-use of blank nodes is complex and issues such as termination [5], minimisation [9, 11], and negation [6] are studied in current research.

As often, the encodings used to demonstrate such high expressive powers in theory papers [2] are not practical, yet they assure us that existential rules could be used to express even the most complicated ontological inference procedures over a knowledge graph. More applied works have shown that one can really solve some very hard (non-polynomial) tasks in this way [4, 8]. Moreover, even beyond its computational benefits, value invention provides us with a crucial facility for adding new *auxiliary* elements to knowledge graphs, which can be required, e.g., to encode contextual information (such as temporal validity) in RDF graphs [7, 12]. In spite of the long history of existential rules in data exchange research (where they are known as *tuple-generating dependencies*), this capability of rules to perform complex data transformations is hardly explored in knowledge graphs yet. For example, a set of a few dozen existential rules suffices to convert the RDF encoding of an OWL EL ontology into a set of normalised ontology axioms that share common sub-expressions.[3]

All of this has already been implemented, e.g., using the existential rule engine VLog [3]. Nevertheless, the vision of replacing our reliable (but largely decommissioned) tooling of ontological reasoning by a more flexible, rule-based inference mechanism is still far from being realised. Prime challenges remain usability (for designing rule-based computations), scalability to knowledge graph sizes, and the ability of handling noise

[3] *Practical Uses of Existential Rules in Knowledge Representation*: tutorial at ECAI 2022; instructions and examples at https://iccl.inf.tu-dresden.de/web/Rules_Tutorial_2020/en.

and context-dependent inferences. In addition, the new ecosystem will need explanation and debugging services, and approaches for adding in other modes of computation that are relevant on knowledge graphs (e.g., based on graph embeddings, network analysis, or graph neural networks). The Semantic Web community will be needed to help invent and analyse the necessary tools and methods, but also to provide their expertise on building good knowledge models that ensure interoperability (of machines) and shared understanding (among humans).

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AI Ethics in the Semantic Web

Francesca Rossi

IBM Research, Yorktown Heights, NY, USA
Francesca.Rossi2@ibm.com

Abstract. AI is going to bring huge benefits in terms of scientific progress, human wellbeing, economic value, and the possibility of finding solutions to major social and environmental problems. Supported by AI, we will be able to make more grounded decisions and to focus on the main values and goals of a decision process rather than on routine and repetitive tasks. However, such a powerful technology also raises some concerns, related for example to the black-box nature of some AI approaches, the possible discriminatory decisions that AI algorithms may recommend, and the accountability and responsibility when an AI system is involved in an undesirable outcome. Also, since many successful AI techniques rely on huge amounts of data, it is important to know how data are handled by AI systems and by those who produce them. These concerns are among the obstacles that hold AI back or that cause worry for current AI users, adopters, and policy makers. Without answers to these questions, many will not trust AI, and therefore will not fully adopt it nor get its positive impact. In this talk I will present the main issues around AI ethics, some of the proposed technical and non-technical solutions, as well as practical actions and regulations being defined for AI development, deployment, and use. I will also highlight the relevance of some AI ethics issues to the Semantic Web.

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