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a. REPORT	b. ABSTRACT	c. THIS PAGE			Feng Chen
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RPPR Final Report
as of 13-Feb-2020

Agency Code:

Proposal Number: 70946CS **Agreement Number: W911NF-17-2-0129**
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Country: USA
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Report Date: 19-Nov-2019 Date Received: 22-Nov-2019
Final Report for Period Beginning 16-Jul-2017 and Ending 19-Nov-2019
Title: Uncertainty Management for Dynamic Decision Making
Begin Performance Period: 16-Jul-2017 **End Performance Period:** 19-Nov-2019
Report Term: 0-Other
Submitted By: Feng Chen Email: fchen5@albany.edu
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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 1 **STEM Participants:** 6

Major Goals: There are two goals in this project:

1. Measure uncertainty in beliefs considering multiple root causes of uncertainty: We extend an existing belief model, called Subjective Logic (SL), to measure uncertainty in beliefs based on the root causes of uncertainty, including lack of information or knowledge, vagueness, and ambiguity. Although SL is developed to deal with the dimension of uncertainty explicitly unlike the existing belief models, SL considers uncertainty derived from lack of information and vagueness but does not deal with ambiguity derived from conflicting evidence.

2. Reduce uncertainty in data with high scalability: We develop scalable uncertainty reduction algorithms by identifying the minimum set of data features to maximize decision effectiveness. A decision-maker often loses high utility by delaying a decision due to numerous alternative decisions with an equal utility or a high volume of uncertain evidence. Our goal is to significantly reduce uncertainty using a minimum set of features while maximizing classification accuracy.

Accomplishments: I summarize our main activities, specific objectives, significant results, and key outcomes as follows:

(1) Our main research activities for the project include:

(1.a) Characterization of uncertainty derived from different root causes (FUSION 2018).

In this work, we study different types of uncertainty in subjective opinions based on the internal belief mass distribution and the base rate distribution. We define fundamental uncertainty characteristics of a given opinion depend on its ‘singularity’, ‘vagueness’, ‘vacuity’, ‘dissonance’, ‘consonance’ and ‘monosonance’ in the formalism of SL and show how these characteristics can be manifested in the three different opinion classes which are binomial, multinomial, and hyper-opinions.

(1.b) Scalable prediction of uncertainty using subjective logic (BigData 2017, TIST 2019)

To enhance scalability and prediction accuracy of unknown opinions in SL, we take a hybrid approach by combining SL with Probabilistic Soft Logic (PSL) (BigData 2017). PSL provides collective reasoning with high scalability based on relationships between opinions but does not deal with uncertainty. By taking the merits of both SL and PSL, we propose a probabilistic logic algorithm, called Collective Subjective Logic (CSL) that provides high

scalability and high prediction accuracy while dealing with uncertain opinions.

We further propose an enhanced model of CSL, namely, CS++, whose opinion inference performance is highly resilient against vacuity and conflicting evidence (TIST 2019). CSL++ achieves high resilience against multidimensional uncertainty in vacuity and conflicting evidence, leading to high prediction accuracy in opinion inference with highly uncertain opinions.

(1.c) Deep learning-based scalable prediction of uncertainty in both statistic and dynamic network data (ICDM 2018, MILCOM 2018, BigData 2018, ICLR 2020-a, AAAI Symposium Series 2019).

In this work, we propose several deep learning (DL)-based opinion inference models to handle node-level opinions explicitly in a large-scale network using graph convolutional neural network (GCN) and variational autoencoder (VAE) techniques (ICDM 2018, MILCOM 2018). This work is the first that leverages the merits of both DL (i.e., GCN and VAE) and a belief model (i.e., SL) to achieve non-parametric learning with low complexity.

We further extend our proposed DL-based model and propose a DL-based dynamic opinion inference model for dynamic network data (BigData 2018). Our proposed approach addresses the three main limitations of existing methods: (1) a lack of scalability; (2) limited capability to handle heterogeneous topological and temporal dependencies among node-level opinions; and (3) high sensitivity to conflicting evidence.

The above methods are limited to the prediction of binary opinions in network data. In the following work, we focus on the prediction of multinomial opinions in network data (ICLR 2020-a). In particular, we propose a Bayesian deep learning framework reflecting various types of uncertainties for classification predictions by leveraging the powerful modeling and learning capabilities of GNNs. We consider multiple uncertainty types in both deep learning (DL) and belief/evidence theory domains. We treat the predictions of a Bayesian GNN (BGNN) as nodes' multinomial subjective opinions in a graph-based on Dirichlet distributions where each belief mass is a belief probability of each class.

The above methods are still limited to the prediction of binary and multinomial opinions in network data. In the following work, we study the performance of a state-of-the-art DL method, namely, evidential neural networks (ENN), for prediction of uncertainty in non-network datasets (e.g., images) (AAAI Symposium Series 2019). We propose an enhanced approach, called regularized ENN, that learns an ENN based on regularizations related to different characteristics of inherent data uncertainty.

(1.d) Scalable prediction of uncertainty under adversarial attacks (BigData 2019)

In this work, we propose a highly scalable opinion inference probabilistic model, namely Adversarial Collective Opinion Inference (Adv-COI), which provides a solution to infer unknown opinions with high scalability and robustness under the presence of uncertain, adversarial evidence by enhancing Collective Subjective Logic (CSL) which is developed by combining SL and Probabilistic Soft Logic (PSL).

(1.e) Active data selection for DL-based uncertainty prediction (ICLR 2020-a: Under review)

In this work, we present a novel multi-source uncertainty prediction approach that enables DL-based models to be actively trained with much less labeled data. By leveraging
SL, we conduct evidence-based theoretical analysis and formally decompose the
predicted entropy over multiple classes into two distinct sources of uncertainty:
vacuity and dissonance, caused by a lack of evidence and conflict of strong evidence,
respectively.

(2) The specific research objectives of this project include:

(2.a) Measure uncertainty in beliefs considering multiple root causes of uncertainty. We extend an existing belief model, called Subjective Logic (SL), to measure uncertainty in beliefs based on the root causes of uncertainty, including lack of information or knowledge, vagueness, and ambiguity.

(2.b) Reduce uncertainty in data with high scalability. We develop scalable uncertainty reduction algorithms by identifying the minimum set of data objects and features to maximize decision effectiveness.

The major activities in (1.a), (1.c), and (1.d) are conducted for the first research objective. The major activities in (1. b), (1.c), and (1.e) are conducted for the second research objective. We note that the major activities in (1.c) are conducted to address both the research objectives. In particular, our proposed DL models can do feature and data section implicitly and can effectively predict uncertainty in beliefs based on the root causes of uncertainty, including lack of information or knowledge, vagueness, and ambiguity.

(3) The significant results include:

(3.a) SL based methods can be effectively extended to measure uncertainty in beliefs based on the root causes of uncertainty, including a lack of information or knowledge, vagueness, and ambiguity. This is a significant result of our research activities in (1.a)

(3.b) SL based methods can be optimized to support a scalable and collective inference of uncertainty of a large set of decision variables in network data. This is a significant result of our research activities in (1.b).

(3.c) SL based methods can be optimized to support a robust inference of uncertainty against adversarial attacks. This is a significant result of our research activities in (1.d).

(3.d) DL based methods are more effective but less efficient than SL based methods for prediction of uncertainty in complex network data. This is a significant result of our research activities in (1.c).

(3.e) DL models to be actively trained with much less labeled data for prediction of uncertainty derived from different root causes. This is a significant result of our research activities in (1.e).

(4) The key outcomes developed include:

(4.a) Novel definitions of fundamental uncertainty characteristics of a given opinion depend on its ‘singularity’, ‘vagueness’, ‘vacuity’, ‘dissonance’, ‘consonance’ and ‘monosonance’ in the formalism of SL

(4.b) Scalable SL-based methods for prediction of binary subjective opinions in network data.

(4.c) Scalable SL-based methods that are robust against adversarial attacks in network data.

(4.d) Effective DL-based methods for prediction of both binary and multinomial subjective opinions in network data.

(4.e) A DL-based active learning method for prediction of multinomial subjective opinions in network data with a small set of labeled data.

Training Opportunities: In the past two years, we hired a total of three graduate assistants to work on the project and three other graduate students also participated in the project. These six students gained rich training in the design and development of new machine learning and deep learning techniques for uncertain management to support dynamic decision making, scholarly writing, and team coordination. We held weekly project meetings to review existing methods in the current literature, discuss the design of new techniques, plan and review research activities, and analyze the data, with the PI as an active participant who provides timely mentoring and feedback. Meeting notes, design documents, and research resources are shared online through Dropbox.

Results Dissemination: We have presented our research work to the general audience in the following conferences: BigData 2017, MILCOM 2018, BigData 2018, BigData 2019, Fusion 2018, Fusion 2019, ICDM 2018, and AAAI Symposium Series 2019. In addition, by giving seminar talks, we have disseminated our project to students, researchers, and teachers in six universities, including Michigan State University, University of Florida, Boston University, University of Delaware, the University of Texas at Dallas, and Missouri University of Science and Technology.

Honors and Awards: Nothing to Report

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Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Faculty
Participant: Jin-Hee Cho 2657769
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Adil Alim
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Xujiang Zhao
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Shu Hu
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Yuzhe Ou
Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: baojian Zhou
Person Months Worked: 6.00 **Funding Support:**

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Chunpai Wang
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
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Other Collaborators:

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Article Title: CSL+: Scalable Collective Subjective Logic under Multidimensional Uncertainty
Authors: Adil Alim, Jin-Hee Cho, and Feng Chen
Keywords: uncertainty, subjective opinion, vacuity, conflicting evidence, opinion inference
Abstract: Using unreliable information sources generating conflicting evidence may lead to a large uncertainty which significantly hurts decision-making process. Recently many approaches have been taken to integrate conflicting data from multiple sources and/or fusing conflicting opinions from different entities. To explicitly deal with uncertainty, a belief model called Subjective Logic (SL), as a variant of Dumpster-Shafer Theory (DST), has been proposed to represent subjective opinions and to merge multiple opinions by offering a rich volume of fusing operators, which have been used to solve many opinion inference problems in trust networks. However, the operators of SL are known to be lack of scalability in inferring unknown opinions from large network data as a result of the sequential procedures of merging multiple opinions. In addition, SL does not consider deriving opinions in the presence of conflicting evidence. In this work, we propose a hybrid inference method that combines SL and Pr
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CONFERENCE PAPERS:

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Paper Title: Deep Learning based Scalable Inference of Uncertain Opinions
Authors: Xujiang Zhao; Feng Chen; Jin-Hee Cho
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Conference Location: LAX Marriott, Los Angeles
Paper Title: Uncertainty-Based Opinion Inference on Network Data Using Graph Convolutional Neural Networks
Authors: Xujiang Zhao, Feng Chen, Jin-Hee Cho
Acknowledged Federal Support: **Y**

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Conference Name: IEEE International Conference on Big Data (BigData'17)
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Paper Title: Collective subjective logic: Scalable uncertainty-based opinion inference
Authors: Feng Chen, Chunpai Wang, Jin-Hee Cho
Acknowledged Federal Support: **Y**

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Conference Name: IEEE International Conference on Big Data (BigData'18)
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Paper Title: Deep Learning for Predicting Dynamic Uncertain Opinions in Network Data
Authors: Xujiang Zhao, Feng Chen, Jin-Hee Cho
Acknowledged Federal Support: **Y**

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Conference Name: IEEE International Conference on Information Fusion (FUSION'18)
Date Received: 31-Aug-2018 Conference Date: 10-Jul-2018 Date Published: 10-Jul-2018
Conference Location: Cambridge, London
Paper Title: Uncertainty Characteristics of Subjective Opinions
Authors: Audun Jøsang, Jin-Hee Cho, and Feng Chen
Acknowledged Federal Support: **N**

Publication Type: Conference Paper or Presentation **Publication Status:** 2-Awaiting Publicat
Conference Name: International Conference on Information Fusion (FUSION 2019)
Date Received: 27-Oct-2019 Conference Date: 02-Jul-2019 Date Published:
Conference Location: Ottawa, Canada
Paper Title: Uncertainty-based Decision Making using Deep Reinforcement Learning
Authors: Xujiang Zhao , Shu Hu, Jin-Hee Cho, and Feng Chen
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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2019 IEEE International Conference on Big Data (IEEE Big Data 2019)
Date Received: Conference Date: 09-Dec-2019 Date Published:
Conference Location: Los Angeles, CA
Paper Title: Uncertainty-Aware Opinion Inference Under Adversarial Attacks
Authors: Adil Alim, Xujiang Zhao, Jin-Hee Cho, and Feng Chen
Acknowledged Federal Support: **Y**

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Date Received: 28-Oct-2019 Conference Date: 26-Apr-2020 Date Published:
Conference Location: Addis Ababa, Ethiopia
Paper Title: Uncertainty-aware Prediction for Graph Neural Networks
Authors: Xujiang Zhao, Feng Chen, Hu Shu, Jin-Hee Cho
Acknowledged Federal Support: **Y**

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Conference Name: International Conference on Learning Representations (ICLR 2020)
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Conference Location: Addis Ababa, Ethiopia
Paper Title: Evidence-aware entropy decomposition for active deep learning
Authors: Wei Shi, Xujiang Zhao, Feng Chen, Qi Yu
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 3-Accepted
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Date Received: 28-Oct-2019 Conference Date: 07-Nov-2019 Date Published:
Conference Location: Washington, DC
Paper Title: Quantifying Classification Uncertainty using Regularized Evidential Neural Networks
Authors: Xujiang Zhao, Yuzhe Ou, Lance Kaplan, Feng Chen, Jin-Hee Cho
Acknowledged Federal Support: **Y**

Nothing to report in the uploaded pdf (see accomplishments)