

Programming Interactive Worlds with Linear Logic

Chris Martens

CMU-CS-15-134
September 2015

School of Computer Science
Carnegie Mellon University
Pittsburgh, PA 15213

Thesis Committee:

Frank Pfenning, Co-chair
Karl Crary, Co-chair
André Platzer
Roger Dannenberg
Anne-Gwenn Bosser

*Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy.*

Copyright © 2015 Chris Martens

This research was sponsored by the National Science Foundation under grant numbers CCF-0546550, CNS-0716469, DGE-0750271; Qatar National Research Fund under grant number NPRP-096671100; and Commission of the European Communities under grant number FP-6506909. The views and conclusions contained in this document are those of the author and should not be interpreted as representing the official policies, either expressed or implied, of any sponsoring institution, the U.S. government or any other entity.

Keywords: Programming Languages, Computational Logic, Game Design, Interactive Simulation, Interactive Storytelling, Interactive Fiction

Abstract

Interactive storytelling weaves together deep computational ideas with humanity’s rich history of story and play, providing an important context for tools and languages to be built. At the same time, formal specification languages offer a palette of representation and inference techniques typically reserved for the analysis of programming languages and complex deductive systems. This thesis connects problems in the interactive storytelling domain to solutions in formal specification.

Specifically, we examine narrative from a structural point of view and observe that alternative narrative paths play a complementary role to simultaneous interacting timelines. *Linear logic* provides the representational tools necessary to investigate this structure, and by extending the correspondence to proofs and proof construction, we find a suite of computational possibilities. We present three efforts toward realizing those possibilities: (1) the use of linear logic programming to *generate* narratives; (2) a new programming language for authoring *interactive* narratives, games, and simulations; and (3) techniques for stating and proving design-level program properties.

We find that linear logic programming, enriched with a minimal extension to its logical semantics, enables a wide range of programming idioms and domain encodings. As evidence, we give five case studies, including social simulation, combat-based adventure games, and board games. To support reasoning about design correctness, we present techniques for stating and proving program invariants, as well as a decidability proof for automatically checking those invariants for a large fragment of the language.

These findings show that linear logic is a fruitful representation language to serve as the basis for modeling and executing interactive worlds, and they invite future investigations on using proof-theoretic methodologies for creative systems.

Acknowledgments

I am tremendously privileged to have been able to do a Ph.D. thesis on the beautiful subjects of logic and game design, and a tremendous number of people contributed toward my ability to do this strange and wonderful thing.

My advisors Frank and Karl have been instrumental every step of the way: from supporting my case for admission to CMU's graduate program, to training me in the foundations of my field, to keeping their minds open as I began to explore these highly unconventional applications of said foundations. Bob Harper's lectures and writings have also been a crucial part of my programming languages education.

Gwenn Bosser's work on linear logic for narrative structure gave me the solid stepping-stone I needed to bring this thesis to fruition, and her collaboration and encouragement has been critical for sustaining my optimism around the project. I also thank David Renshaw for pointing out her papers to me in the first place.

My other collaborators in papers, programs, and creative media, have given me so much energy and inspiration: João Ferreira, William Lovas, Rob Simmons, Vincent Zeng, Elizabeth Davis, Will Byrd, Claire Alvis, Philip Gianfortoni, Ben Blum, Lea Albaugh, Jamie Perconti, Tom Murphy VII, Salil Joshi, Andrew Cave, Kaustuv Chaudhuri, Dale Miller, Daniel Spoonhower: I thank you all for your patience with me as an often-fickle collaborative partner, and for the joy you've shared with me in what we created.

I thank the many attentive readers of this work (and its predecessors), including, of course, my thesis committee members—André and Roger in particular have contributed insightful advice on accessibility to audiences outside of logic. Other readers I thank include William Cohen, Nico Feltman, Adam Smith, Joe Osborn, Jurie Horneman, Paul Mazaitis, and several anonymous reviewers, whose feedback has invariably strengthened my understanding of prior work, communication of my own work, and inspiration for future work.

The CMU POP/ConcertRG student group has provided valuable discussion of papers, talks, and their own research, as well as attentive feedback on my own talks and papers. In particular, my classmates Arbob Ahmed and Henry DeYoung have motivated me with their fascinating research and deep analytical insights, and Ian Voysey provided incredibly thorough and helpful feedback on practice talks. The crew that graduated early in my time in grad school—Neel Krishnaswami, Noam Zeilberger, Jason Reed, William

Lovas, Rob Simmons, and Dan Licata—set an admirable tone for humble and patient research discussions that I tried to emulate after they graduated (it's harder than it looks). Current students like Nico Feltman, Joe Tassarotti, and Anna Gommerstadt have spiritually succeeded them with the proactive collaboration and careful thoughtfulness they bring to the group—I can't wait to see what they do next.

Ron Garcia, Ed Morehouse, and Stephanie Balzer, during their postdocs at CMU, have all provided valuable mentorship and research discussions. Gillian Smith and Jessica Hammer, although my relationships with both of them are relatively new, have been immensely helpful in me considering my career trajectory and imagining the sort of professor I might be someday. I feel incredibly lucky to have benefited from the mentorship of these wonderful people.

Will Byrd approached me at OPLSS in 2010 and, out of the blue, asked if I "knew anything about interactive fiction" because I came from CMU like (renowned IF author) Andrew Plotkin. We then shared hunches about logical formalisms for IF and put together a paper for OBT about it—long before I pursued the possibility of a thesis about the idea. Will has since been a wonderful collaborator and mentor, emailing me unprompted and frequently with opportunities, suggestions, and encouragement.

Independently-created games by Emily Short, Porpentine, Stephen Lavelle, Terry Cavanaugh, Squinky, Lydia Neon, Tom 7, Sam Barlow, Andrew Plotkin, Andi McClure, Michael Brough, Aaron Reed, and Merritt Kopas, have provided a great deal of creative inspiration for this thesis work. My students in 98-228 Interactive Fiction helped me, too, with their appreciation and insight for the works I assigned them to play, and the wonderful games they turned in as final assignments.

The UC Santa Cruz EIS lab, and the INT and FDG conference attendees, have helped me understand what games research can be, and that it is full of wonderful people. Conversations, papers, and talks by Kate Compton, Gillian Smith, Squinky, Clara Fernandez-Vara, Joe Osborn, James Ryan, Aaron Reed, Jacob Garbe, April Grow, Michael Mateas, Noah Wardrip-Fruin, Ian Horswill, Gail Carmichael, R. Michael Young, and Ben Kybartas, have been crucial to the joy I find in games and creativity research.

Back at home in Pittsburgh, there are a few who've stuck with me across the years: Lea Albaugh, who met me 11 years ago and lived with me for 6, patiently taught me things about Inform 7, sewing, soldering, and intersectional feminism. Lea's thumb on the pulse of local art and theater projects is also what led me to see the play *Tamara*, the study of which has been my favorite application of this thesis work. William Lovas, who persuaded me during one pivotal bike ride in 2012 to pursue my "linear logic for games" idea, despite my doubts that my advisor would take it seriously, has been there for me in countless ways, over countless drinks and meals, in countless cities across the world.

There have been several people in my life who pushed me to meet a higher bar of excellence than I was meeting before their intervention, but the first person to push me beyond what I thought I was capable of was Jamie Morgenstern, all but dragging me across the finish line of my first 5k race in 2010 to finish in under 26 minutes. She then proceeded to achieve elite status in her own running career and finish her Ph.D. in under 5 years, providing an inspirational (if unattainable) watermark for achievement.

For someone like me who's often timid about face-to-face interaction, internet communication channels are absolutely priceless, and the friendships I've made and/or maintained through LiveJournal and Twitter deserve just as much recognition as the few I've grown close to in physical space. Kat Hagan, Lindsey Kuper, Cass Sparks, Jason Reed, Danielle Kefford, Greg Hanneman, Katie Mazaitis, Tim Chevalier, Joshua Dunfield, Mym Johnson, Akiva Leffert, Annie Ogborn: your words have helped me in so, so many ways. And then there's Philip "8" Gianfortoni, whose weekly video calls are the only form of regular long-distance, voice-based contact I've ever maintained, and I'm so grateful for his part in sustaining them.

There's still an unfortunate stigma against addressing mental health in academia, and I'm going to try to do my part to break it here: I would unquestionably not have finished my Ph.D. without therapy for anxiety and depression. Thanks to Dr. W for her incredible skills.

I also would not have been able to afford my undergraduate education at CMU (an undeniably critical stepping stone to grad school there) without almost full grant support from the US Department of Education, for which I am immensely grateful. Furthermore, I doubt I would have been admitted in the first place without the groundbreaking work of Allan Fisher and Jane Margolis, 20 years ago, to identify and excise the irrelevant gender-correlated criteria previously associated with computer science talent in CMU's undergraduate admissions.

My paternal grandmother died in 2013, after she gave me 27 years of unwavering love; a brilliant, hilarious spirit as a role model; and stories and artifacts pertaining to my father, who died a few months after my birth. I only wish she could be here to see me graduate.

My mother has been the one constant in my life, and she has made her love known the whole way. Growing up, my "village" consisted of grandparents, aunts and uncles, teachers, and my mother's romantic partners, all of whose love and guidance deserve my profound thanks. But my mother shaped who I am today more than anyone else; it's hard to thank her without a touch of narcissism. Mom: thanks for showing me how to be fearless, opinionated, independent, creative, hard-working, vulnerable, selfless and selfish (as the situation warrants).

Finally, while it is clearly *possible* to be a successful academic without a partner who shoulders a large burden of domestic and emotional labor, it is abundantly clear to me that Rob's efforts to be an equitable and generous

partner to me while juggling his own teaching career have made a huge difference in my productivity, creativity, and happiness. And furthermore, I am in the rare position to have a partner who understands and enjoys my thesis work, even to the point of putting up with my rambling about narrative structure after every television show, movie, and play we see together.

Thanks, everyone, for your patience, insight, love, and support.

Contents

1	Introduction	1
1.1	Potential Narratives	4
1.2	Generative Systems	5
1.3	Thesis Goals	7
1.4	Approach	9
1.4.1	Preliminary Definitions	9
1.4.2	Linear Logic	10
1.4.3	Logic Programming	10
1.4.4	Logical Frameworks	11
1.5	Contributions	12
2	Linear Logic for Narrative Structure	15
2.1	Introduction	15
2.2	Modeling Narratives	16
2.2.1	Linear Logic by Example	18
2.3	Linear Logic	19
2.3.1	Intuitionistic Linear Logic: Sequent Calculus	22
2.3.2	Some Derivation Examples	23
2.4	Alternative and Simultaneous Story Structure	25
2.4.1	Alternative Storylines	25
2.4.2	Simultaneous Storylines	28
2.4.3	Alternatives and Simultaneity in Linear Logic	29
2.4.4	Proofs as Stories	31
2.5	First-Order Linear Logic	34
2.6	Related Work	35
2.6.1	Planning	35
2.6.2	Petri Nets	36
2.7	Conclusion	38
3	Linear Logic Programming for Narrative Generation	39
3.1	Introduction	39
3.2	Linear Logic Programming	40
3.2.1	Forward and Backward Chaining	40
3.2.2	Logic Programming: Proof Search as Execution	41

3.2.3	Celf	43
3.3	Example: A Romantic Tragedy Story World	45
3.3.1	Initial State	49
3.3.2	Program Query	50
3.4	(Forward-Chaining) Proofs as (Causally-Structured) Stories	51
3.4.1	Automated Causal Graph Production	55
3.5	Playable Traces	57
3.6	Related Work	59
3.7	Conclusion	60
4	Cepre: A Linear Logic Language for Interactive Programs	61
4.1	Background	61
4.1.1	New Syntax	62
4.2	Stages and Interactivity	63
4.3	Staged Logic Programming	67
4.3.1	Rule Ordering	68
4.3.2	Negation	69
4.3.3	Finite Set Comprehension	70
4.3.4	Summarization	71
4.4	Sensing and Acting Predicates	72
4.5	Language Definition	74
4.6	Interpreting Other Systems	79
4.6.1	Kodu	79
4.6.2	PuzzleScript	81
4.6.3	Featherweight Inform 7	84
4.7	Implementation	88
4.8	Related Work	88
4.9	Conclusion	89
5	Case Studies	91
5.1	Refining an Interactive Social Story World	92
5.1.1	Story World Overview	92
5.1.2	Code	93
5.1.3	Sample Interaction	102
5.1.4	Discussion	104
5.2	Dungeon Crawler	106
5.2.1	Game Design Goals	106
5.2.2	Iteration 1	107
5.2.3	Iteration 2	108
5.2.4	Discussion	111
5.3	Settlers of Catan	112
5.3.1	Game Rules	112
5.3.2	Discussion of the Game's Design	115
5.3.3	Iteration 1	116

5.3.4	Iteration 2	117
5.3.5	Discussion	124
5.3.6	Potential Analyses	126
5.4	Garden Simulator	127
5.4.1	Game Idea	127
5.4.2	Iteration 1	127
5.4.3	Iteration 2	129
5.4.4	Iteration 3	132
5.4.5	Discussion	136
5.5	Tamara	137
5.5.1	Tamara's Story, Script, and Rules	137
5.5.2	Encoding the Script Structure	138
5.5.3	Compilation to Twine	148
5.5.4	Discussion	151
5.6	Discussion of Case Studies	151
5.6.1	Limitations	153
5.6.2	Strengths	153
5.6.3	Potential	154
5.6.4	Analyzing Game Dynamics	155
6	Reasoning About Linear Logic Programs	157
6.1	Introduction	157
6.1.1	Example: Blocks World	157
6.2	Meta-Linear Logic	159
6.2.1	Example: Tower of Hanoi	163
6.2.2	Potential for Automation	165
6.2.3	Limitation: Recursive Predicates	167
6.3	Consumptive Invariants	168
6.3.1	Backward-Chaining Linear Logic Programs	168
6.3.2	Example: Linked List Shape Analysis	169
6.3.3	Potential for Automation	169
6.3.4	Limitation: Apartness Constraints	169
6.4	Generative Invariants	170
6.4.1	Example: Generative Signature for Blocks World	171
6.4.2	Generative Property Preservation	171
6.4.3	Potential for Automation	172
6.4.4	Limitations	174
6.5	Decidability of Invariant Checking for the Propositional Fragment	174
6.5.1	The Propositional Fragment	175
6.5.2	A Tricky Example	176
6.5.3	Vector Addition Systems	177
6.5.4	Presburger Vector Addition Systems	179
6.5.5	Flat(able) Generative Invariants	180
6.5.6	Computing Presburger reachability sets	181

6.5.7	The Algorithm	181
6.5.8	End-to-End Example	182
6.5.9	Adequacy and Correctness	184
6.6	Conclusion	185
6.6.1	Limitation: Instance-Dependent Invariants	185
7	Conclusion	187
7.1	Contributions	188
7.1.1	Game and Narrative Design	188
7.1.2	Programming Languages and Logic	189
7.2	Future Work	190
7.2.1	Narrative Representation	190
7.2.2	Generative Methods	191
7.2.3	Accessible Game Design Tools	192
7.2.4	Reasoning Tools	193
7.3	Final Remarks	193
A	CLF Semantics	195
B	Ceptre Typing and Kinding Rules	197
C	Code Listings	199
C.1	First Past the Post Voting Protocol	199
C.2	Sokoban	200
C.3	Tower of Hanoi	203
	Bibliography	205

List of Figures

1.1	Sample interaction with the game <i>Adventure</i> by Will Crowther.	2
1.2	Sample interaction with <i>Galatea</i> with state display tool enabled.	6
1.3	Screenshot of <i>Prom Week</i> demonstrating character interaction options.	7
2.1	Fabula versus Sujet in <i>Memento</i>	16
2.2	Four structural patterns in branching narrative.	27
2.3	Petri net for the simultaneous Three Little Pigs story world.	37
4.1	Screenshots of command-line interaction with <i>Ceptr</i>	66
4.2	A level in <i>Lime Rick</i> after several moves.	83
4.3	<i>Inform 7</i> Action Processing Diagram	86
5.1	A trace representing part of the “Once More, With Feeling” episode of <i>Buffy</i>	105
5.2	Settlers of Catan beginner’s starting map.	114
5.3	Two possible play traces under the Settlers building mechanics.	118
5.4	Sample map for second iteration of Settlers of Catan encoding.	120
5.5	Trace graph for part of a Settlers of Catan playthrough.	125
5.6	Partial trace graph for first garden simulator iteration.	130
5.7	Partial trace graph for second garden simulator iteration.	133
5.8	Partial trace graph for third garden simulator iteration.	136
5.9	Excerpt from the script of <i>Tamara</i>	139
5.10	Trace graph for <i>Tamara</i> encoding, part 1.	146
5.11	Trace graph for <i>Tamara</i> encoding, part 2.	147
6.1	Generative trace structure	173

