

Contents

Acknowledgments	v
Abstract	vii
Zusammenfassung	ix
1 Introduction	1
1.1 Motivation	1
1.2 Transprecision Computing	2
1.3 Open-Source Instruction-Set Architecture	4
1.4 Outline	6
1.5 Contributions	7
1.6 List of Publications	8
2 Exploring Transprecision Computing	11
2.1 Introduction	11
2.2 Primer on Floating-Point Arithmetic	13
2.2.1 IEEE 754 Floating-Point	14
2.2.2 Considerations for FP in Hardware	18
2.3 Extensions to the FP Type System	19
2.3.1 Floating-Point Types And Programming Flow	20
2.3.2 Transprecision Floating Point Unit Prototype .	25
2.3.3 Experimental Results	27
2.3.4 Related Work	35
2.4 Alternatives to FP Arithmetics: Unum	37
2.4.1 Properties of Unums	38

2.4.2	Considerations for Unum in Hardware	40
2.5	Alternatives to FP Arithmetics: Posit	43
2.5.1	Properties of Posits	43
2.5.2	Considerations for Posit in Hardware	46
2.6	Summary and Conclusion	48
3	An Open-Source Transprecision FPU	51
3.1	Introduction	51
3.2	Architecture	53
3.2.1	Requirements	53
3.2.2	Building Blocks	55
3.2.3	Configuration, Parametrization, and Usage	60
3.3	Enabling FPnew in the RISC-V ISA	61
3.3.1	FP Formats	61
3.3.2	Operations	63
3.3.3	Scalar Extensions	63
3.3.4	Vectorial Extension	64
3.3.5	Auxiliary Operations Extension	65
3.3.6	Encoding	65
3.3.7	Compiler Support	66
3.4	Programming of TP Application Kernels	68
3.4.1	Transprecision Application Case Study	68
3.4.2	Compiler Support	72
3.5	Related Work	72
3.5.1	SIMD and TP in Commercial ISAs	72
3.5.2	Open-Source Configurable FPU Blocks	74
3.5.3	FPU for RISC-V	75
3.5.4	Novel Arithmetics / TP FP Accelerators	75
3.5.5	Multi-Mode Arithmetic Blocks	76
3.5.6	Other uses of our TP-FPU	79
3.6	Summary and Conclusion	79
4	Transprecision FP in the Embedded Domain	81
4.1	Introduction	81
4.2	Embedded SoC for Transprecision	83
4.2.1	System Architecture	85
4.2.2	SoC Implementation	88
4.2.3	Benchmarking	92

4.3	Augmenting RI5CY with FPnew	97
4.3.1	Integration	97
4.3.2	Implementation Results	98
4.4	Embedded TP Cluster Architectures	101
4.4.1	Architecture and Implementation	104
4.4.2	Software Infrastructure	112
4.4.3	Experimental Results	114
4.4.4	Comparison with the SoA	125
4.4.5	Related Work	126
4.5	Notable Embedded Systems Using FPnew	132
4.6	Summary and Conclusion	137
5	Transprecision FP in the High-Performance Domain	139
5.1	Introduction	139
5.2	Application-Class TP Computing	140
5.2.1	Integration	141
5.2.2	Silicon Implementation	142
5.2.3	Implementation Results	145
5.2.4	Application Performance Study	151
5.2.5	Comparison to the State of the Art	153
5.3	Data Center Scale Embedded TP Computing	154
5.3.1	Agile Transprecision Software Development	154
5.3.2	XwattPilot Cloud System	155
5.3.3	Implications for HP & Embedded Co-Execution	158
5.4	Notable HP Class Systems Using FPnew	159
5.4.1	Snitch	159
5.4.2	Ara	159
5.4.3	European Processor Initiative	160
5.5	Summary and Conclusion	160
6	Conclusions	163
6.1	Main Results	164
6.2	Outlook	167
A	Chip Gallery	169
A.1	Treated in This Thesis	170
A.2	Further Implementations of FPnew	174
A.3	Miscellaneous ASICs	177

B Acronyms	179
Bibliography	181
Curriculum Vitae	199