Transformations for polyhedral process networks

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Bibliography

[1] M. Adiletta, M. Rosenbluth, and D. Bernstein. The next generation of Intel IXP network processors. *Intel Technology Journal*, 06(03), 15 aug 2002.

[2] A. V. Aho, R. Sethi, and J. D. Ullman. *Compilers: principles, techniques, and tools*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, 1986.

[3] T. W. Ainsworth and T. M. Pinkston. On characterizing performance of the Cell Broadband Engine Element Interconnect Bus. In *NOCS '07: Proceedings of the First International Symposium on Networks-on-Chip*, pages 18–29, 2007.

[4] R. Bagnara, P. M. Hill, and E. Zaffanella. The Parma Polyhedra Library: Toward a complete set of numerical abstractions for the analysis and verification of hardware and software systems. *Sci. Comput. Program.*, 72(1-2):3–21, 2008.

[5] F. Balarin, Y. Watanabe, H. Hsieh, L. Lavagno, C. Passerone, and A. Sangiovanni-Vincentelli. Metropolis: An integrated electronic system design environment. *Computer*, 36(4):45–52, 2003.

[6] U. K. Banerjee. *Dependence Analysis for Supercomputing*. Kluwer Academic Publishers, Norwell, MA, USA, 1988.

[7] C. Bastoul. Code generation in the polyhedral model is easier than you think. In *PACT '04: Proceedings of the 13th International Conference on Parallel Architectures and Compilation Techniques*, pages 7–16, 2004.

[8] S. Bhattacharrya, R. Leupers, J. Takala, and E. Deprettere, editors. *Handbook on signal processing systems*, chapter by Verdoolaege, S., Polyhedral process networks. Springer, 2010.

[9] S. S. Bhattacharyya and E. A. Lee. Scheduling synchronous dataflow graphs for efficient looping. *J. VLSI Signal Process. Syst.*, 6(3):271–288, 1993.

[10] A. Bik, M. Girkar, P. Grey, and X. Tian. Efficient exploitation of parallelism on Pentium III and Pentium 4 processor-based systems. *Intel Technology Journal Q1 (March) (2001) 1-9*, 2001.

[11] G. Bilsen, M. Engels, R. Lauwereins, and J. Peperstraete. Cyclo-static dataflow. *IEEE Transactions on signal processing*, 44(2):397–408, 1996.

[12] W. Blume, R. Eigenmann, K. Faigin, J. Grout, J. Hoeflinger, D. A. Padua, P. Petersen, W. M. Pottenger, L. Rauchwerger, P. Tu, and S. Weatherford. Polaris: Improving the effectiveness of parallelizing compilers. In *LCPC '94: Proceedings of the 7th International Workshop on Languages and Compilers for Parallel Computing*, pages 141–154, 1995.

[13] U. Bondhugula, A. Hartono, J. Ramanujam, and P. Sadayappan. A practical automatic polyhedral parallelizer and locality optimizer. *SIGPLAN Not.*, 43(6):101–113, 2008.

[14] P. M. Carpenter, A. Ramirez, and E. Ayguade. Mapping stream programs onto heterogeneous multiprocessor systems. In *CASES '09: Proceedings of the 2009 international conference on Compilers, architecture, and synthesis for embedded systems*, pages 57–66, 2009.

[15] J. Ceng, J. Castrillon, W. Sheng, H. Scharwächter, R. Leupers, G. Ascheid, H. Meyr, T. Isshiki, and H. Kunieda. MAPS: an integrated framework for MP-SoC application parallelization. In *DAC '08: Proceedings of the 45th annual Design Automation Conference*, pages 754–759, 2008.

[16] S. Chakraborty, S. Kunzli, and L. Thiele. A general framework for analysing system properties in platform-based embedded system designs. In *DATE '03: Proceedings of the conference on Design, Automation and Test in Europe*, page 10190, Washington, DC, USA, 2003. IEEE Computer Society.

[17] E. Cheung, H. Hsieh, and F. Balarin. Automatic buffer sizing for rate-constrained KPN applications on multiprocessor system-on-chip. In *Proc. of HLDVT*, pages 37–44, 2007.

[18] P. Clauss. Counting solutions to linear and nonlinear constraints through Ehrhart polynomials: applications to analyze and transform scientific programs. In *ICS '96: Proceedings of the 10th international conference on Supercomputing*, pages 278–285, 1996.

[19] P. Clauss. Handling memory cache policy with integer points counting. In *Euro-Par '97: Proceedings of the Third International Euro-Par Conference on Parallel Processing*, pages 285–293, 1997.

[20] P. Clauss, V. Loechner, and D. Wilde. Deriving formulae to count solutions to parameterized linear systems using Ehrhart polynomials: Applications to the analysis of nested-loop programs, 1997.

[21] R. Dömer, A. Gerstlauer, J. Peng, D. Shin, L. Cai, H. Yu, S. Abdi, and D. D. Gajski. System-on-chip environment: a SpecC-based framework for heterogeneous MPSoC design. *EURASIP J. Embedded Syst.*, 2008:1–13, 2008.

[22] B. K. Dwivedi, A. Kumar, and M. Balakrishnan. Automatic synthesis of system on chip multiprocessor architectures for process networks. In *Proc. of CODES+ISSS*, pages 60–65, 2004.

[23] J. Falk, J. Keinert, C. Haubelt, J. Teich, and S. S. Bhattacharyya. A generalized static data flow clustering algorithm for MPSoC scheduling of multimedia applications. In *Proc. of EMSOFT*, pages 189–198, 2008.

[24] P. Feautrier. Parametric integer programming. *RAIRO Recherche Operationnelle*, 22, 1988.

[25] P. Feautrier. Dataflow analysis of array and scalar references. *International Journal of Parallel Programming*, 20, 1991.

[26] J. A. Fisher. Very long instruction word architectures and the ELI-512. In *ISCA '83: Proceedings of the 10th annual international symposium on Computer architecture*, pages 140–150, 1983.

[27] M. P. Forum. MPI: A Message-Passing Interface standard. Technical report, 1994.

[28] D. D. Gajski, F. Vahid, S. Narayan, and J. Gong. *Specification and design of embedded systems*. Prentice-Hall, Inc., 1994.

[29] L. George and M. Blume. Taming the IXP network processor. In *PLDI '03: Proceedings of the ACM SIGPLAN 2003 conference on Programming language design and implementation*, pages 26–37, 2003.

[30] A. H. Ghamarian, M. C. W. Geilen, T. Basten, and S. Stuijk. Parametric throughput analysis of synchronous data flow graphs. In *Proc. of DATE*, pages 116–121, 2008.

[31] M. I. Gordon, W. Thies, and S. Amarasinghe. Exploiting coarse-grained task, data, and pipeline parallelism in stream programs. In *ASPLOS-XII: Proceedings of the 12th international conference on Architectural support for programming languages and operating systems*, pages 151–162, 2006.

[32] M. I. Gordon, W. Thies, M. Karczmarek, J. Lin, A. S. Meli, A. A. Lamb, C. Leger, J. Wong, H. Hoffmann, D. Maze, and S. Amarasinghe. A stream compiler for communication-exposed architectures. In *ASPLOS-X: Proceedings of the 10th international conference on Architectural support for programming languages and operating systems*, pages 291–303, 2002.

[33] K. Grüttner and W. Nebel. Modelling program-state machines in SystemC. In *FDL*, pages 7–12, 2008.

[34] M. Gschwind, H. P. Hofstee, B. Flachs, M. Hopkins, Y. Watanabe, and T. Yamazaki. Synergistic processing in cell's multicore architecture. *IEEE Micro*, 26(2):10–24, 2006.

[35] S. Ha, C. Lee, Y. Yi, S. Kwon, and Y.-P. Joo. Hardware-software codesign of multimedia embedded systems: the PeaCE. In *RTCSA '06: Proceedings of the 12th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications*, pages 207–214, 2006.

[36] M. W. Hall, J. M. Anderson, S. P. Amarasinghe, B. R. Murphy, S.-W. Liao, E. Bugnion, and M. S. Lam. Maximizing multiprocessor performance with the SUIF compiler. *Computer*, 29(12):84–89, 1996.

[37] C. A. R. Hoare. Communicating sequential processes. *Commun. ACM*, 21(8):666–677, 1978.

[38] J. Y. Hur, S. Wong, and T. Stefanov. Design trade-offs in customized on-chip crossbar schedulers. *J. Signal Process. Syst.*, 58(1):69–85, 2010.

[39] J. A. Kahle, M. N. Day, H. P. Hofstee, C. R. Johns, T. R. Maeurer, and D. Shippy. Introduction to the Cell multiprocessor. *IBM J. Res. Dev.*, 49(4/5):589–604, 2005.

[40] G. Kahn. The Semantics of a Simple Language for Parallel Programming. In *Proc. of the IFIP Congress 74*. North-Holland Publishing Co., 1974.

[41] T. Kangas, P. Kukkala, H. Orsila, E. Salminen, M. Hännikäinen, T. D. Hämäläinen, J. Riihimäki, and K. Kuusilinna. UML-based multiprocessor SoC design framework. *ACM Trans. Embed. Comput. Syst.*, 5(2):281–320, 2006.

[42] J. Keinert, M. Streubuehr, T. Schlichter, J. Falk, J. Gladigau, C. Haubelt, J. Teich, and M. Meredith. SystemCoDesigner—an automatic ESL synthesis approach by design space exploration and behavioral synthesis for streaming applications. *ACM Trans. Des. Autom. Electron. Syst.*, 14(1):1–23, 2009.

[43] K. Kennedy and J. R. Allen. *Optimizing compilers for modern architectures: a dependence-based approach*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 2002.

[44] B. Kienhuis, E. F. Deprettere, P. v. d. Wolf, and K. A. Vissers. A methodology to design programmable embedded systems - the y-chart approach. In *Embedded Processor Design Challenges: Systems, Architectures, Modeling, and Simulation - SAMOS*, pages 18–37, 2002.

[45] A. Kumar, S. Fernando, Y. Ha, B. Mesman, and H. Corporaal. Multiprocessor systems synthesis for multiple use-cases of multiple applications on FPGA. *ACM Trans. Des. Autom. Electron. Syst.*, 13(3):1–27, 2008.

[46] J.-Y. Le Boudec and P. Thiran. *Network calculus: a theory of deterministic queuing systems for the internet*. Springer-Verlag New York, Inc., New York, NY, USA, 2001.

[47] E. A. Lee and D. G. Messerschmitt. Synchronous data flow. In *Proceedings of the IEEE*, volume 75, pages 1235–1245, September 1987.

[48] C. Lemke. The dual method of solving the linear programming problem. *Naval Research Logistics Quarterly*, 1:36 – 47, 1954.

[49] L. Li, B. Huang, J. Dai, and L. Harrison. Automatic multithreading and multiprocessing of C programs for IXP. In *PPoPP '05: Proceedings of the tenth ACM SIGPLAN symposium on Principles and practice of parallel programming*, pages 132–141, 2005.

[50] S. Meijer, B. Kienhuis, J. Walters, and D. Snuijf. Automatic partitioning and mapping of stream-based applications onto the Intel IXP network processor. In *SCOPES '07: Proceedingsof the 10th international workshop on Software & compilers for embedded systems*, pages 23–30, 2007.

[51] S. Meijer, H. Nikolov, and T. Stefanov. On compile-time evaluation of process partitioning transformations for Kahn process networks. In *CODES+ISSS '09: Proceedings of the 7th IEEE/ACM international conference on Hardware/software codesign and system synthesis*, pages 31–40, 2009.

[52] S. Meijer, H. Nikolov, and T. Stefanov. Combining process splitting and merging transformations for polyhedral process networks. In *Proc. of the 8th Int. IEEE Workshop on Embedded Systems for Real-Time Multimedia (ESTIMedia)*, pages 97–106, 2010.

[53] S. Meijer, H. Nikolov, and T. Stefanov. Throughput modeling to evaluate process merging transformations in polyhedral process networks. In *Proceedings of the conference on Design, automation and test in Europe (DATE'10)*, pages 747–752, 2010.

[54] B. Meister, A. Leung, N. Vasilache, D. Wohlford, C. Bastoul, and R. Lethin. Productivity via automatic code generation for PGAS platforms with the R-Stream compiler. In *APGAS'09 Workshop on Asynchrony in the PGAS Programming Model*, June 2009.

[55] A. Moonen, M. Bekooij, R. v. d. Berg, and J. v. Meerbergen. Practical and accurate throughput analysis with the cyclo static dataflow model. In *Proc. of MASCOTS*, pages 238–245, 2007.

[56] G. E. Moore. Cramming more components onto integrated circuits. *Electronics*, 38(8):114–117, April 1965.

[57] S. Muchnick. *Advanced Compiler Design and Implementation*. Morgan Kaufmann Publishers, Inc., 1997.

[58] D. Nadezhkin, S. Meijer, T. Stefanov, and E. Deprettere. Realizing FIFO communication when mapping Kahn process networks onto Cell. In *SAMOS IX: International Symposium on Systems, Architectures, MOdeling and Simulation*, 2009.

[59] J. Nickolls, I. Buck, M. Garland, and K. Skadron. Scalable parallel programming with CUDA. *Queue*, 6(2):40–53, 2008.

[60] H. Nikolov, T. Stefanov, and E. Deprettere. Multi-processor system design with ESPAM. In *Proc. of CODES+ISSS*, pages 211–216, 2006.

[61] H. Nikolov, T. Stefanov, and E. Deprettere. Systematic and automated multiprocessor system design, programming, and implementation. *Computer-Aided Design of Integrated Circuits and Systems, IEEE Transactions on*, 27(3):542–555, 2008.

[62] H. Nikolov, M. Thompson, T. Stefanov, A. Pimentel, S. Polstra, R. Bose, C. Zissulescu, and E. Deprettere. Daedalus: toward composable multimedia MP-SoC

design. In *DAC '08: Proceedings of the 45th annual conference on Design automation*, pages 574–579, 2008.

[63] L. noel Pouchet, C. Bastoul, A. Cohen, and N. Vasilache. Iterative optimization in the polyhedral model: Part I, one-dimensional time. In *International Symposium on Code Generation and Optimization (CGO)*, pages 144 – 156, 2007.

[64] "OpenCL". "the open standard for parallel programming of heterogeneous systems http://www.khronos.org/opencl/", 2009.

[65] S. Pakin. Receiver-initiated message passing over RDMA networks. *Parallel and Distributed Processing, 2008. IPDPS 2008. IEEE International Symposium on*, pages 1–12, April 2008.

[66] K. K. Parhi and D. G. Messerschmitt. Static Rate-Optimal Scheduling of Iterative Data-Flow Programs via Optimum Unfolding. *IEEE Transaction on Computers*, 40(2):178–195, Feb. 1991.

[67] A. D. Pimentel, C. Erbas, and S. Polstra. A systematic approach to exploring embedded system architectures at multiple abstraction levels. *IEEE Trans. Comput.*, 55(2):99–112, 2006.

[68] J. Pino, S. Bhattacharyya, and E. A. Lee. A hierarchical multiprocessor scheduling framework for Synchronous Dataflow Graphs. Technical Report UCB/ERL M95/36, EECS Department, University of California, Berkeley, 1995.

[69] S. Pop, A. Cohen, C. Bastoul, S. Girbal, G. A. Silber, and N. Vasilache. Graphite: Loop optimizations based on the polyhedral model for gcc. In *Proc. of the 4th GCC Developper's Summit*, pages 179–198, June 2006.

[70] L.-N. Pouchet, C. Bastoul, A. Cohen, and J. Cavazos. Iterative optimization in the polyhedral model: part ii, multidimensional time. In *PLDI '08: Proceedings of the 2008 ACM SIGPLAN conference on Programming language design and implementation*, pages 90–100, 2008.

[71] W. Pugh and D. Wonnacott. An exact method for analysis of value-based array data dependences. In *Proceedings of the 6th International Workshop on Languages and Compilers for Parallel Computing*, pages 546–566, 1994.

[72] K. H. Rosen. *Discrete mathematics and its applications (2nd ed.)*. McGraw-Hill, Inc., New York, NY, USA, 1991.

[73] M. S. Schlansker and B. R. Rau. EPIC: Explicitly parallel instruction computing. *Computer*, 33(2):37–45, 2000.

[74] A. Schrijver. *Theory of linear and integer programming*. John Wiley & Sons, Inc., New York, NY, USA, 1986.

[75] N. Shah, W. Plishker, K. Ravindran, and K. Keutzer. Np-click: A productive software development approach for network processors. *IEEE Micro*, 24(5):45–54, 2004.

[76] J. Sjodin, S. Pop, H. Jagasia, T. Grosser, and A. Pop. Design of graphite and the polyhedral compilation package. 2009.

[77] S. Sriram and S. Bhattacharyya. *Embedded Multiprocessors: Scheduling and Synchronization*. Marcel Dekker, Inc., 2000.

[78] T. Stefanov. Converting weakly dynamic programs to equivalent process network specifications, 2004. PhD thesis, Leiden University.

[79] T. Stefanov, B. Kienhuis, and E. Deprettere. Algorithmic transformation techniques for efficient exploration of alternative application instances. In *Proc. of CODES*, pages 7–12, 2002.

[80] S. Stuijk, M. Geilen, and T. Basten. Exploring trade-offs in buffer requirements and throughput constraints for synchronous dataflow graphs. In *DAC '06: Proceedings of the 43rd annual Design Automation Conference*, pages 899–904, 2006.

[81] S. Stuijk, M. Geilen, and T. Basten. Throughput-buffering trade-off exploration for Cyclo-Static and Synchronous Dataflow Graphs. *IEEE Trans. Comput.*, 57(10):1331–1345, 2008.

[82] N. N. S. Technologies. http://www.network-speed.com.

[83] J. Teich and L. Thiele. Exact Partitioning of Affine Dependence Algorithms. *Lecture Notes in Computer Science (LNCS), Springer*, 2268:133–151, 2002.

[84] L. Thiele, I. Bacivarov, W. Haid, and K. Huang. Mapping applications to tiled multiprocessor embedded systems. In *ACSD '07: Proceedings of the Seventh International Conference on Application of Concurrency to System Design*, pages 29–40, 2007.

[85] L. Thiele, S. Chakraborty, and M. Naedele. Real-time calculus for scheduling hard real-time systems. In *ISCAS*, pages 101–104, 2000.

[86] L. Thiele and N. Stoimenov. Modular performance analysis of cyclic dataflow graphs. In *EMSOFT 09: Proceedings of the 9th ACM international conference on Embedded software*, pages 127–136, Grenoble, France, 2009.

[87] W. Thies, M. Karczmarek, and S. P. Amarasinghe. StreamIt: A language for streaming applications. In *CC '02: Proceedings of the 11th International Conference on Compiler Construction*, pages 179–196, 2002.

[88] M. Thompson and A. D. Pimentel. Towards multi-application workload modeling in Sesame for system-level design space exploration. In *SAMOS*, pages 222–232, 2007.

[89] A. Turjan. Compiling nested loop programs to process networks, 2007. PhD thesis, Leiden University, The Netherlands.

[90] A. Turjan, B. Kienhuis, and E. Deprettere. Translating affine nested-loop programs to process networks. In *CASES '04: Proceedings of the 2004 international conference on Compilers, architecture, and synthesis for embedded systems*, pages 220–229, 2004.

[91] S. van Haastregt and B. Kienhuis. Automated synthesis of streaming C applications to process networks in hardware. In *DATE*, pages 890–893, 2009.

[92] S. Verdoolaege. *Incremental Loop Transformations and Enumeration of Parametric Sets*. PhD thesis, Katholieke Universiteit Leuven, 2005.

[93] S. Verdoolaege. An integer set library for program analysis. *ACES symposium, Edegem, 7-8 september*, 2009.

[94] S. Verdoolaege, M. Bruynooghe, G. Janssens, and F. Catthoor. Multi-dimensional incremental loop fusion for data locality. In *In Proceedings of the IEEE International Conference on Application Specific Systems, Architectures, and Processors*, pages 17–27, 2003.

[95] S. Verdoolaege, H. Nikolov, and T. Stefanov. pn: a tool for improved derivation of process networks. *EURASIP J. Embedded Syst.*, 2007(1):19–19, 2007.

[96] S. Verdoolaege and K. Woods. Counting with rational generating functions. *J. Symb. Comput.*, 43(2):75–91, 2008.

[97] S. Verdoolaege, K. M. Woods, M. Bruynooghe, and R. Cools. Computation and manipulation of enumerators of integer projections of parametric polytopes. CW Reports CW392, K.U.Leuven, Department of Computer Science, Mar. 2005.

[98] D. K. Wilde. A library for doing polyhedral operations. Technical Report RR-2157.

[99] X. D. Zhang, Q. J. Li, R. Rabbah, and S. Amarasinghe. A lightweight streaming layer for multicore execution, http://cag.lcs.mit.edu/commit/papers/07/zhang-dascmp07.pdf.

Index

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