Institution: University of Edinburgh

Unit of Assessment: 11

Title of case study: Code size reduction enables cost savings and enhances functionality of modem and WiFi chipsets

Period when the underpinning research was undertaken: 2005 – 2019

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Murray Cole	Professor	1990 – present
Björn Franke	Reader	2003 – present
Hugh Leather	Reader	2009 – present
Michael O'Boyle	Professor	1997 – present

Period when the claimed impact occurred: 2014 – 2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

Research led by the University of Edinburgh (UoE) has resulted in a compiler tool that reduces firmware code size by up to 12% in modem chips for smartphones and Internet of Things (IoT) devices. The research has been commercialised by world-leading smartphone chip manufacturer Qualcomm, and employed in more than 175,000,000 5G handsets worldwide. It enabled the company to bring to market modem chips that are smaller, more energy efficient, and/or able to perform more complex functions (such as compatibility with 5G) than previously possible. As an early adopter of the open-sourced UoE research, Qualcomm's business has significantly improved, borne out both in their clients' ability to manufacture devices with novel functionality, and in their elimination of competitors from the 5G modem chip market.

2. Underpinning research

Compilers are crucial software tools supporting the modem chips that power smart devices, translating source code into binary that can be executed by the modem's processor. As smart devices become ever more complex, compiler optimisation has become an area of increasing focus for the chip industry, allowing modem chips either to improve functionality while maintaining their size, or to reduce their size while maintaining functionality (aiding the development of micro-devices).

The University of Edinburgh (UoE)'s Compiler and Architecture Design group (CArD) has conducted research into compiler optimisation over a period of 15 years. They have led investigations into exploiting architectural idiosyncrasies in processors [3.1], source-level transformations [3.2], exploiting compact instruction modes [3.3], and novel methods of reducing code size [3.4, 3.5].

In 2013, while conducting research for [3.4], CArD became involved in the LLVM open-source compiler community, an umbrella project of academic and commercial researchers investigating theoretical and practical improvements of the widely used open-source LLVM compiler framework. As a result of CArD's contributions to the project, a collaboration with chip manufacturer Qualcomm emerged, wherein CArD would use Qualcomm's Hexagon chips to

challenge and advance their research into the specific problem of reducing code size in modem chips. Qualcomm's interest was the opportunity to reduce production costs and create higher-functioning products by optimising their code size. Dr Björn Franke of CArD led a team that included Pranav Bhandarkar and Anshuman Dasgupta from Qualcomm Innovation Center and UoE PhD student Tobias Edler von Koch.

In [3.4] the UoE team observed that binary executables generated by compilers from the source code of applications often contain copies and near-copies of functions with the same or similar functionality. These were often the result of poor software engineering practices (e.g. "copy & paste") and suboptimal programming language design (e.g. C++ templates that re-instantiate classes for each parameter type). Using a novel graph-based similarity measure, presented in [3.4, section 2], the UoE team discovered that approximately 15% of the total executable code of an application is contained in functions which are at least 95% similar. While many compilers contain passes or "plug-ins" aimed at the removal of duplicate functions, none had yet attempted the removal of **almost** identical functions. This novel idea could viably reduce code size to levels not previously achieved.

The team developed an LLVM compiler pass to test their theory. Functions were initially sorted by their "degree of similarity". Then, given that a certain threshold was reached, two or more functions were merged into a single instance. The team evaluated their technique using industry benchmarks (SPEC CPU2006) and three target platforms (Intel x86, Qualcomm's ARM based Krait CPU, and Qualcomm's Hexagon DSP as used in WiFi/modem chipsets) [3.4, section 3]. Across the benchmarks the team observed average code size reductions of 4%, with individual benchmarks showing reductions of up to 11.5%. The testing figures were exceeded upon applying the pass to Qualcomm's Hexagon firmware, where the team achieved 12% reduction in code size [5.6]. This was the first time such techniques had been successful while maintaining a device's functionality and performance and requiring no custom hardware to execute.

The LLVM compiler pass developed by the team has now become part of Qualcomm's standard code generation tool for the LLVM-based compiler used in their Hexagon Software Development Kit (SDK) [5.6]. Since 2014 it has been used for generating firmware deployed to billions of cellular and WiFi modems in IoT devices, smartphones and tablets [5.6].

3. References to the research

3.1. Franke, B. (2013). C Compilers and Code Optimization for DSPs. In S. S. Bhattacharyya, E. F. Deprettere, R. Leupers, & J. Takala (Eds.), *Handbook of Signal Processing Systems* (pp. 1015-1040). Springer New York. https://doi.org/10.1007/978-1-4614-6859-2_31 **(4 citations)**

3.2. Franke, B., O'Boyle, M., Thomson, J., & Fursin, G. (2005). Probabilistic Source-level Optimisation of Embedded Programs. In *Proceedings of the 2005 ACM SIGPLAN/SIGBED Conference on Languages, Compilers, and Tools for Embedded Systems* (pp. 78-86). (LCTES '05). New York, NY, USA: ACM. https://doi.org/10.1145/1065910.1065922 **(80 citations; LCTES '05 acceptance rate 27%)**

3.3. Edler von Koch, T. J. K., Bohm, I., & Franke, B. (2010). Integrated instruction selection and register allocation for compact code generation exploiting freeform mixing of 16- and 32-bit instructions. In *Proceedings of the 8th annual IEEE/ACM international symposium on Code Generation and Optimization* (CGO '10) (pp. 180-189). LOS ALAMITOS: Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1145/1772954.1772980 **(14 citations; CGO '10 acceptance rate 30%)**

3.4. Edler von Koch, T. J. K., Franke, B., Bhandarkar, P., & Dasgupta, A. (2014). Exploiting Function Similarity for Code Size Reduction. In *Proceedings of the 2014 SIGPLAN/SIGBED*

Conference on Languages, Compilers and Tools for Embedded Systems (pp. 85-94). New York, NY, USA: ACM. https://doi.org/10.1145/2597809.2597811 **(19 citations; LCTES '14 acceptance rate 27%)**

3.5. Rocha, R., Petoumenos, P., Wang, Z., Cole, M., & Leather, H. (2019). Function Merging by Sequence Alignment. In *Proceedings of the 2019 International Symposium on Code Generation and Optimization* (pp. 149-163). Washington DC, USA: Institute of Electrical and Electronics Engineers (IEEE). https://dl.acm.org/doi/10.5555/3314872.3314892 **(Best paper award; 7 citations; CGO '19 acceptance rate 30%)**

Citation counts obtained from Google Scholar 2020-12-03.

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4. Details of the impact

The compiler pass developed by the University of Edinburgh (UoE) team, and integrated into the Hexagon SDK, led to a chain of impacts that benefitted not only Qualcomm's business, but also the business of their clients, and the end-users of billions of smart devices that now employ the technology.

Qualcomm is one of the world's leading suppliers of 3G, 4G and now 5G enabled System-on-a-Chip products, under the Snapdragon brand. In 2019, the company was the global leader for all smartphone processors, enjoying a 40% share of a USD4,800,000,000 (11-2019) market [5.1]. Their clients in the smartphone industry include Apple, Xiaomi, Samsung [5.2] and Motorola [5.3]. Meanwhile the company's processors for IoT devices are sold to many of the world's top 10 IoT manufacturers including Tesla [5.3], Gemalto, Telit and Quectel [5.4]. In 2015, shortly after UoE research was implemented, Qualcomm shipped a total of 923,000,000 chips [5.5, para. 2]. Since then, the company have sustained large shipment figures and in 2019 Qualcomm confirmed shipment of 1,000,000 modem chips **per day** for IoT devices alone [5.6, para. 2].

Qualcomm used the novel UoE compiler pass to reduce the size of the embedded software on all their recent cellular modems and WiFi chipsets. Two key improvements in Qualcomm's product line attributable to the code size reduction technique are chips of the same size as their predecessors with increased functionality, and chips that are smaller and more energy efficient than their predecessors but with the same functionality. Qualcomm confirm the research has had "significant impact" on their business, and state:

> *[The UoE compiler pass] results in up to 12% reduction in code size, which directly translates into cost savings due to the comparatively high cost of memory relative to the cost of processing elements. It plays a critical part in ensuring that the extremely strict code size requirements dictated by Qualcomm's business needs are met.* [5.6, para. 2]

One of the most significant improvements in functionality enabled by the compiler pass is compatibility with 5G. The 5G software stack has a larger memory footprint than its predecessors; however, increasing chip size to accommodate this would have led to larger, more expensive devices and/or reduced device battery life. The UoE technology helped Qualcomm to maintain chip size (and therefore device size) as well as device battery life, while meeting the demands required for 5G. Qualcomm explain that:

> *[with] the development of ever more advanced modem chipsets that interface with next-generation cellular networks…cutting-edge research into software tools, such as the work conducted by Dr Björn Franke and his group at the University of Edinburgh, will continue to have high impact on our technology roadmap.* [5.6, paras. 3-4]

Program memory, dictated by code size, takes up the greatest amount of physical space on a modem chip. By reducing the physical space needed for memory, the size of the chip is reduced, thus more chips can be made on a single wafer of silicon. Due in part to the 12% code size reduction, Qualcomm have reported that their chips are "50% smaller and more cost-effective" and "engineered to reduce power consumption by up to 70% in idle mode" [5.4, para. 2]. While one benefit of this is the ability to power increasingly tiny devices, such as smart watches and rings, the immediate economic boost to Qualcomm comes via the reduction in chip production costs that smaller chips bring.

These benefits pass positive impacts onto Qualcomm's clients. In the press release unveiling the 2018 9205 LTE Modem, IoT clients Quectel and Telit stated:

> *All its features are put together in a tiny and very energy-efficient chipset that will help Quectel to offer LTE IoT modules that are powerful, economical and with support for superb battery life.* [5.4, antepenultimate para.]
>
> *The multimode, highly integrated capabilities of the Qualcomm 9205 LTE modem allow us to reduce power consumption and module footprint giving our customers the ability to design and deploy smaller, battery-powered devices that work worldwide on virtually any cellular IoT network.* [5.4, penultimate para.]

The 5G chip market was worth USD1,100,000,000 (05-2020) in 2019 [5.7, para. 1]. The same year, Forbes named Qualcomm the market leader in 5G: "If you look at which company has the most products out in the market and the one with the most complete 5G mobile solutions, it's pretty much no contest." [5.8, penultimate para.]. It is estimated that in 2020 the UoE technology was employed in 175,000,000 to 225,000,000 5G handsets [5.9, antepenultimate para.].

Since UoE's key contribution to the improved Hexagon SDK, Qualcomm has asserted its dominance in the chip market. Their overwhelming success is exemplified by the renewal of Qualcomm's contract with Apple in 2019, following a high-profile court dispute. After Qualcomm launched their improved chips, their key competitor, Intel, announced their withdrawal from the mobile 5G modem market, an acknowledgement that they could no longer compete. Apple, who had been poised to contract Intel as chip supplier for their iPhone line, reverted to using Qualcomm chips [5.10].

Acting on UoE research, Qualcomm's business has significantly improved, the benefits of which have reached a host of clients collectively worth millions of USD, plus billions of end-users of smart devices and IoT technology.

5. Sources to corroborate the impact

5.1. Strategy Analytics: Q2 2019 Smartphone Apps Processor Market Share: AI Chips Show Strong Growth. (2019, November 14). Retrieved June 15, 2020, from https://www.businesswire.com/news/home/20191114005625/en/Strategy-Analytics-Q2-2019-Smartphone-Apps-Processor

5.2. Nellis, S. (2019, December 3). Xiaomi, Oppo to use Qualcomm's newest mobile phone chips - Netscape Money & Business. Retrieved June 12, 2020, from https://www.compuserve.com/pf/story/0002/20191203/KBN1Y72CZ_2?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZ29vZ2xlLmNvLnVrLw&guce_referrer_sig=AQAAABAA84xpt1zKEMnVouyMyI7VAXjhAbLLvWqckAezww2mNQ2i-0kWz9Ox_9PlWEltCdaMh4jgTylEVMIqR2a1C8KLEQj_bJpiTlh0TS0v1QR6ZsXFu5Tm6udmAA_Lkfm1stKAV3wMIuyITloTvcs9-Igh1xjpNE4bQzQXZykVab8B

5.3. Qualcomm: Company's Customers Expenditure Growth Rates. (2020, October 22). Retrieved October 22, 2020, from https://csimarket.com/stocks/custexNO.php?markets&code=QCOM

5.4. Qualcomm Introduces Next-Gen Cellular Chipset Purpose-Built for IoT. (2018, December 17). Retrieved June 12, 2020, from https://www.qualcomm.com/news/releases/2018/12/17/qualcomm-introduces-next-gen-cellular-chipset-purpose-built-iot

5.5. Sag, A. (2015, November 13). Qualcomm Reinvigorates Snapdragon With New Snapdragon 820 SoC. Retrieved June 30, 2020, from https://www.forbes.com/sites/moorinsights/2015/11/13/qualcomm-reinvigorates-snapdragon-with-new-snapdragon-820-soc/

5.6. Letter of corroboration from Principal Engineer/Manager, Qualcomm Innovation Center, Inc.

5.7. Global 5G Chipset Market Share Report, 2020-2027. (2020, May). Retrieved June 15, 2020, from https://www.grandviewresearch.com/industry-analysis/5g-chipset-market

5.8. Moorhead, P. (2019, June 12). Who Is 'Really' Leading In Mobile 5G, Part 2: 5G Mobile Chipsets. Retrieved June 15, 2020, from https://www.forbes.com/sites/patrickmoorhead/2019/06/12/who-is-really-leading-in-mobile-5g-part-2-5g-mobile-chipsets/

5.9. Horwitz, J. (2019, November 8). Samsung and Mediatek emerge as Qualcomm's top 5G chip rivals in 2020. Retrieved June 15, 2020, from https://venturebeat.com/2019/11/08/samsung-and-mediatek-emerge-as-qualcomms-top-5g-chip-rivals-in-2020/

5.10. Clark, D., & Wakabayashi, D. (2019, April 16). Apple and Qualcomm Settle All Disputes Worldwide. Retrieved March 5, 2020, from https://www.nytimes.com/2019/04/16/technology/apple-qualcomm-settle.html