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Hot-Rodding the Cortex-A8

Intrinsity Accelerates ARM's Processor With Fast14 Dynamic Logic

By Tom R. Halfhill {7/27/09-01}

ARM's fastest microprocessor core keeps getting faster. Only five months ago, Texas Instruments announced a 1.0GHz ARM Cortex-A8 in future OMAP3 cellphone chips. Now Intrinsity is unveiling a 1.0GHz Cortex-A8 accelerated with dynamic logic. Intrinsity's new core, code-named Hummingbird, is functionally identical to a Cortex-A8 implemented in standard-cell static logic.

Intrinsity says Hummingbird can reach 1.0GHz under worst-case conditions at 1.2V when fabricated in a 45nm-LP low-leakage process. It could exceed that clock frequency in a faster but leakier 45nm-GP generic process. Throughput at 1.0GHz is 2,000 native mips.

According to Intrinsity, power consumption is very low for a processor with this performance. Unfortunately, Intrinsity's lead customer—Samsung Electronics—isn't publicly disclosing power measurements at this time. *Microprocessor Report* estimates that active power at 1.0GHz is less than 750mW, with static leakage in the very low milliwatt range. Low leakage is particularly important for battery-powered mobile systems with intermittent usage patterns, such as cellphones.

Hummingbird gives SoC designers an attractive alternative to conventional implementations of ARM's Cortex-A8 processor. The bad news is that Intrinsity has crafted Hummingbird for one special customer (Samsung), so the core isn't immediately available to anyone else.

The good news is that Intrinsity's agreement with Samsung is nonexclusive, so other customers can license Hummingbird. Intrinsity says it can adapt the core—and port it to a different fabrication process, if necessary—in six months or less. Customers must have a Cortex-A8 license from ARM, because Intrinsity isn't an ARM licensee and can't license the core directly.

Destined for a Future iPhone?

Intrinsity collaborated with Samsung to develop Hummingbird in less than a year. In a press release issued last September, Intrinsity announced an agreement with the South Korean company to develop high-performance, low-power processors using Intrinsity's proprietary Fast14 technology. Samsung says it will use Hummingbird in SoCs for "mobile products," probably 3G and 4G cellphones.

Note that Samsung makes the application processor in the hot-selling Apple iPhone 3GS. Previous iPhones had an ARM11-based Samsung SoC running at 412MHz, but the iPhone 3GS has a Cortex-A8 running at 600MHz. In theory, Samsung could drop Intrinsity's 1.0GHz Hummingbird into the existing design with few or no changes, boosting throughput by 67% without busting the iPhone's power budget.

If our speculation is correct, Samsung's Hummingbird-based SoC will meet TI's OMAP3 head-to-head in the market soon. TI plans to ship an OMAP3 with a 1.0GHz Cortex-A8 later this year. Samsung could ship its 1.0GHz Hummingbird SoC at around the same time. Samsung already has sample chips, and the first-pass silicon booted Linux—a good harbinger for a radically new implementation.

New Phones Need Faster Processors

As smartphones become more popular and ordinary cellphones add more features, designers need faster baseband chips and application processors. Other systems demanding

higher performance are netbooks and mobile Internet devices. ARM has responded by introducing faster, more-sophisticated processor cores, such as the superscalar Cortex-A8 and multicore-ready Cortex-A9 MPCore. (See *MPR 10/25/05-02* and *MPR 11/14/05-01*, "Cortex-A8: High Speed, Low Power.")

Samsung, an ARM Cortex-A8 licensee, needed a processor even faster than ARM's standard-issue Cortex-A8. Using experience with existing implementations as a basis, ARM estimates the Cortex-A8 could exceed 650MHz in a 65nm-LP process or 1.1GHz in a 65nm-GP process. But Samsung didn't want to pay the power-consumption penalty for cranking up the clock speed in a higher-leakage GP process.

This isn't the first time Intrinsity has hot-rodded an ARM processor. In 2007, Intrinsity applied the same technology to the Cortex-R4, producing the swifter Cortex-R4X. (See *MPR 9/24/07-01*, "Cortex-R4X: Extreme Makeover.") At that time, *MPR* speculated that a Fast14 version of the Cortex-A8 would be even more impressive. ARM poured cold water on our enthusiasm, saying that a semicustom implementation of the Cortex-A8 (the Texas Instruments F1, found in TI's OMAP3) was already fast enough.

Apparently, Samsung didn't agree, and Intrinsity was happy to oblige. In addition to accelerating the processor with Fast14 logic, Intrinsity tweaked the core in several other ways, such as optimizing the RTL and using custom SRAMs for the L1 caches. As a result, Hummingbird is a highly customized design.

Intrinsity optimized this implementation for Samsung's design rules and target fabrication process—specifically, Common Platform 45nm-LP. (Samsung is a member of the Common Platform alliance; other prominent members are IBM and Chartered Semiconductor.) Intrinsity says that adapting Hummingbird for other customers and porting it to a different foundry would take four to six months. It's easier if customers use a Common Platform process.

Comparing Cortex-A8 Implementations

In an attempt to compare Hummingbird with a conventional implementation of the Cortex-A8, *MPR* studied documentation on the ARM and TI websites and requested additional data from ARM and Intrinsity. Unfortunately, we can't draw fair comparisons in this article.

Samsung is using the Common Platform 45nm-LP process. ARM is estimating performance in different and larger fabrication processes—TSMC 65nm-LP and 65nm-GP. And TI, like Samsung, won't publicly disclose power consumption for the processor cores in its SoCs. Therefore, *MPR* must rely on educated estimates and guidance. Table 1 summarizes the available data and various estimates.

At first glance, ARM's static-logic core appears to have advantages over Intrinsity's dynamic-logic core, especially with regard to active power consumption at 1.0GHz. However, a critical missing factor in this table is current leakage, which can be severe at deep-submicron geometries. GP is much leakier than LP. An apples-to-apples comparison should match GP to GP and LP to LP. Even then, GP and LP technologies vary at different foundries.

Another factor is that ARM's estimates in Table 1 are for a semicustom implementation of the Cortex-A8—not a fully portable, synthesizable RTL model implemented entirely in standard cells. To achieve the performance estimated in Table 1, ARM assumes the licensee will enhance the synthesizable RTL with some custom blocks and semicustom design. ARM created the Cortex-A8 with such enhancements in mind. A purely standard-cell implementation would have worse performance.

Another consideration is that Samsung and Intrinsity have working silicon in 45nm-LP. Samsung prefers conservative specifications that allow higher production yields. ARM's numbers are estimates, though not without grounding in reality—they are based on real-world experience with the Cortex-A8 in TI's popular OMAP chips.

	ARM Cortex-A8	ARM Cortex-A8	Intrinsity Cortex-A8 Hummingbird
Core Implementation	Semicustom, static logic	Semicustom, static logic	Semicustom, Fast14 dynamic logic + static logic
IC Process	TSMC 65nm-LP	TSMC 65nm-GP	Common Platform 45nm-LP
Core Freq	> 650MHz	> 1.1GHz	1.0GHz
Core Area	< 4.0mm²	< 4.0mm²	~ 4.0mm²
Core Voltage	1.2V	1.0V	1.2V
Dynamic Power*	< 383.5mW	< 495mW	< 750mW†
Power Efficiency	< 0.59mW / MHz	< 0.45mW / MHz	< 0.75mW / MHz†

Table 1. Estimated Cortex-A8 performance in different implementations and fabrication processes. Unfortunately, process technology and current leakage are significant uncontrolled variables in this table. Nor are the core areas directly comparable. ARM's estimates include 32KB L1 caches and an L2 cache controller, but not an ARM Neon unit or embedded trace module (ETM). The Hummingbird estimate includes 32KB L1 caches, an L2 cache controller, the Neon unit, and ETM. *Dynamic power consumption is "typical." †*MPR* estimate.

Other Chips Climbing Toward 1.0GHz

At this writing, the fastest Cortex-A8 chips can run at 833MHz and 800MHz. The 833MHz chip is the Samsung S5PC100, rumored to be the application processor in the new iPhone 3GS. (Teardowns by Rapid Repair and PhoneWreck name the S5PC100 as the application processor, but this information has not been confirmed by Apple or Samsung.) Samsung manufactures the S5PC100 in a 65nm-LP process. The 800MHz chip is TI's semicustom implementation of the Cortex-A8 in the OMAP3440, also manufactured in 65nm technology.

TI is promising a faster OMAP3640 chip with a 1.0GHz Cortex-A8 later

this year. TI will manufacture the OMAP3640 and other OMAP36*xx* parts in a new 45nm process—the same geometry, though not the same process, as the Common Platform 45nm-LP technology that Samsung is using for Hummingbird. TI hasn't released core-specific power-consumption estimates for the OMAP3640, so we can't compare those numbers.

As always, keep in mind that "typical" power consumption quoted by vendors isn't verified independently. Measurements heavily depend on the processor's workload, which the vendors rarely specify. Leakage varies at a relatively linear rate with the core area.

It's important that Samsung is manufacturing Hummingbird in a low-leakage LP process. Cellphones and other mobile communication devices typically spend most of their time in sleep mode, not in active use. Static leakage drains the battery, even while the device is inactive. Fabricating a chip in a low-leakage process conserves power, though usually while sacrificing clock speed. A Cortex-A8 implementation such as Hummingbird that can reach 1.0GHz while leaking only a few milliwatts should have a competitive advantage.

Cheaper Than an ARM and a Leg

Intrinsity promotes Hummingbird as a cheaper alternative to an ARM architectural license, the usual path to improving performance over ARM's standard-issue processor cores. Whereas a core license entitles an ARM licensee to use an off-the-shelf ARM core, an architectural license allows the licensee to develop a new microarchitecture compatible with the ARM architecture.

ARM has only a few architectural licensees, some of which are undisclosed. The confirmed list includes Freescale, Intel, Marvell, and Qualcomm. Rumored licensees are Apple and Samsung. (See *MPR 5/26/09-01*, "Why Apple Feels Chipper.")

This club is rather exclusive, because architectural licenses are much more expensive than core licenses. Whereas the entry-level price for an ARM core license is under $1 million, an architectural license reportedly costs about $20 million. And that's just the start. Developing a new ARM-compatible microarchitecture could cost twice that much.

Intrinsity's pitch is that its ARM-compatible implementations will cost much less money than developing a new ARM-compatible microarchitecture—and will require less time, as well. Intrinsity's customer needs only a core license, not an architectural license. The reason is that an Intrinsity Fast14 core is a new implementation, not a new microarchitecture.

At the block-diagram level, Hummingbird is identical to a conventional ARM Cortex-A8. All function units, pipelines, and I/O interfaces are exactly the same. Cycle for cycle, Hummingbird operates just like a regular Cortex-A8, so it's compatible with existing Cortex-A8 chip designs. (Intrinsity calls Hummingbird a "cycle-accurate" implementation of the Cortex-A8.)

To boost performance, Intrinsity replaces ARM's static logic in critical paths with Fast14 logic. Fast14 is Intrinsity's proprietary 1-of-N domino logic (NDL), which uses four-phase overlapped clocking and mostly NMOS transistors. Intrinsity's design tools automatically optimize the size of each transistor to meet specific targets for timing, noise immunity, power consumption, and resistance to electromagnetic interference. Fast14 circuits need no latches or P-channel transistors in the dynamic-logic paths, and they have only four to eight levels of logic in places where a traditional static circuit would have 10 to 20 levels.

Because Fast14 logic gates are 25% to 50% faster than static logic gates, the processor can do more work per clock cycle without altering the basic design of the instruction pipelines and functional blocks. Fast14 is particularly efficient for muxes and other elements with wide structures. Intrinsity also uses optimized static logic, custom circuits, and standard cells. (See *MPR 8/13/01-02*, "Intrinsity's Dynamic Designs.") Figure 1 shows Intrinsity's design flow.

In essence, Intrinsity is optimizing the implementation, not redesigning the core. Therefore, Intrinsity needs no ARM license when working with an ARM core licensee. Intrinsity merely licenses its Fast14 technology, design services, and tools to the ARM Cortex-A8 licensee. The licensee pays chip royalties to both ARM and Intrinsity—an expense far below the cost of obtaining an ARM architectural license and designing a new ARM-compatible microarchitecture.

Intrinsity's Market Outlook

The most likely potential customers for Hummingbird are existing Cortex-A8 licensees. In addition to Samsung, they include Acer, Asustek, Broadcom, Guangzhou Skytone, LG, MSI, Nokia, NXP, STMicroelectronics, and Toshiba. TI is a Cortex-A8 licensee but is already using its semicustom version of the core in OMAP3 chips. (See *MPR 7/24/06-01*, "The F1: TI's 65nm Cortex-A8.") For OMAP4, TI is using the dual-core Cortex-A9 MPCore.

Marvell and Qualcomm are ARM architectural licensees that have already designed new ARM-compatible microarchitectures. Marvell's Feroceon is the only ARM-compatible processor with out-of-order execution. (See *MPR 5/23/05-01*, "Marvell Puts ARM Out of Order.") Qualcomm's new Snapdragon QSD8672 chip for "smartbooks" has two ARM-compatible processor cores running at 1.5GHz. After committing to these expensive designs, it's doubtful that either company is interested in a faster Cortex-A8 from Intrinsity.

Intel, another ARM architectural licensee, is surely even less interested. Intel inherited its ARM license by acquiring DEC's StrongARM group in 1998 but is now positioning the x86 against ARM. (See *MPR 3/30/09-01*, "Intel Will Customize Atom.")

MPR believes Apple is an ARM architectural licensee and is developing a new ARM-compatible processor for the iPhone and other future products. Last year, Apple acquired P.A. Semi, a fabless semiconductor company. Although P.A. Semi used the Power Architecture, the company was founded by engineers who in 1995 developed the famous DEC StrongARM processor—a high-performance, low-power implementation

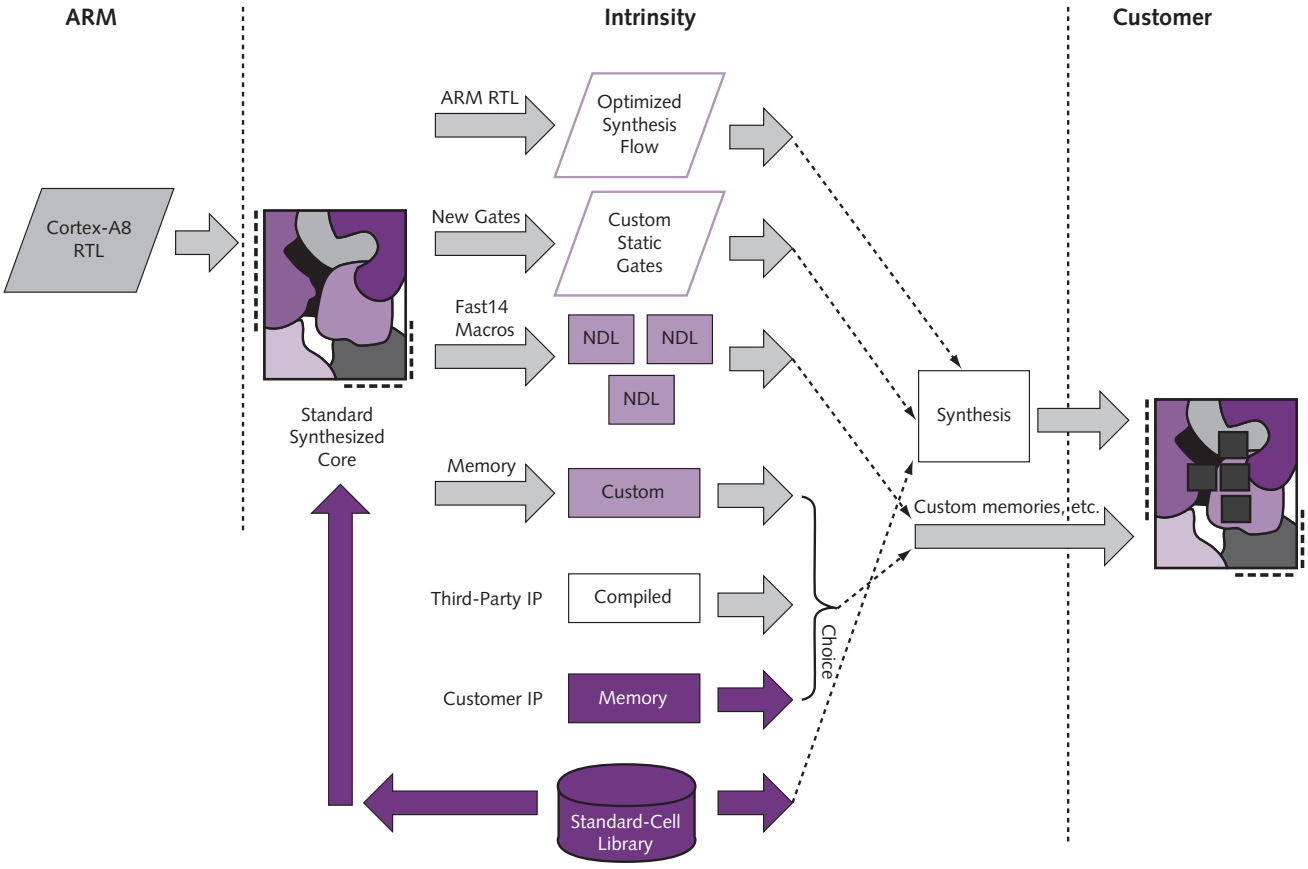

Figure 1. Intrinsity Fast14 design flow. Although Intrinsity has developed proprietary design tools unique to Fast14 dynamic logic, the design flow uses industry-standard tools for some steps, including timing analysis, simulation, and verification.

of the ARM7. Apple has been steadily strengthening its chip-design expertise. (See *MPR 5/26/09-01*, "Why Apple Feels Chipper.")

If our speculation about Apple is correct, a Hummingbird-based application processor from Samsung might be a stop-gap solution until Apple's own ARM-compatible design is ready. If Apple isn't designing its own ARM-compatible core, Samsung's Hummingbird SoC might figure more prominently in Apple's plans. Another possibility is that Apple could design its own ARM-compatible core and accelerate it further with Intrinsity's technology. The combination of a custom ARM-compatible microarchitecture optimized with Fast14 logic could be a real barnstormer.

Regardless of Apple's plans, the big question for other potential Hummingbird customers is whether the core's advantages outweigh its disadvantages. On the upside, Hummingbird should deliver more throughput in a lower-leakage fabrication process than a conventional implementation. On the downside, it costs additional money, requires some porting, creates a dependency on Intrinsity, and shifts technical support from ARM to Intrinsity if something goes wrong. Prospective customers must decide whether the difference in performance outweighs the additional risks.

More Choices Make Better Choices

In any case, Hummingbird is an interesting alternative to a conventional Cortex-A8. It goes even a step beyond the semicustom implementation of the Cortex-A8 that ARM helped develop for TI's OMAP chips.

If nothing else, Hummingbird further demonstrates the flexibility of ARM's business model. Third parties like Intrinsity can try to improve on ARM's designs. Flexibility is becoming more important as ARM faces its toughest competitor yet—Intel.

Intel's June 4 announcement that it will acquire Wind River Systems is another signal that Intel is mounting its most serious assault on the embedded market in years. The $884 million acquisition of an embedded system-software company follows Intel's introduction of the low-power Atom processor, Intel's introduction of Atom-based SoCs, and Intel's collaboration with TSMC to move Atom into custom designs. (See *MPR 3/30/09-01*, "Intel Will Customize Atom," *MPR 8/18/08-01*, "Intel's New SoCs," and *MPR 4/7/08-01*, "Intel's Tiny Atom.")

Yet a major handicap is Intel's reluctance to license an x86 core directly to chip developers. Without a licensable x86, developers are limited to Intel's standard-part SoCs and whatever devices emerge from the TSMC collaboration.

Neither AMD nor VIA Technologies licenses x86 cores, either. Only some ancient x86 designs from the 1970s and 1980s—reimplemented in RTL—are available as licensable intellectual property from third parties. No one can tinker with Intel's x86 processors in the way that Intrinsity is tinkering with ARM's processors.

In addition to having a wide choice of processor cores, configurations, fabrication technologies, and foundries, ARM's licensees now have another option. They can choose between a standard-cell, static-logic implementation of the Cortex-A8 or a highly customized, dynamic-logic implementation of the Cortex-A8.

Having more choices is always advantageous in the embedded market, where every milliwatt of power and square millimeter of silicon can make or break a new design.

Price & Availability

Intrinsity's implementation of the ARM Cortex-A8 processor, code-named Hummingbird, is available now to ARM Cortex-A8 licensees. The initial implementation is intended for the Common Platform 45nm-LP process. Intrinsity says it can port the core to a different fabrication process in four to six months—maybe less, if it's a Common Platform process. Customers will pay the usual chip royalties to ARM and additional royalties to Intrinsity. Intrinsity hasn't publicly disclosed its fees or royalties. For more information, visit: *www.intrinsity.com.*