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Recursive Layout Generation

*Louis M. Monier
Jeremy Dion*

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Recursive Layout Generation

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Abstract

We present a recursive method for generating layout for VLSI chips which combines the flexibility of gate array and standard cell layout with the control and density of custom layout. The method allows seamless integration of hand-drawn and synthesized layout, so that hand layout need only be used where the increase in density is justified. Layout is generated automatically with predictable results; small changes in the source result in small changes of the overall layout. The system is versatile enough to build dense VLSI microprocessor chips automatically.

Table of Contents

1. Introduction	1
2. The Annotated Hierarchical Netlist	1
2.1. Cell Generators	2
2.2. Netlist Traversal	5
3. Layout Generation	5
3.1. Hand-Drawn Cells	6
3.2. Leaf Cells	7
3.3. Composite Cells	8
3.4. Routing	9
3.5. Netlist Hierarchy Equals Layout Hierarchy?	10
4. Results	11
References	13

List of Figures

Figure 1: Cell schematics	3
Figure 2: A Cell Generator	3
Figure 3: Boolean Equations	4
Figure 4: A hand-drawn cell	6
Figure 5: A leaf cell after placement	7
Figure 6: The same leaf cell after routing	7
Figure 7: Layout by Corner Alignment	8
Figure 8: The BIPS-1 64-bit Floating-Point Divider	12
Figure 9: The BIPS-0 Microprocessor	12

1. Introduction

Most effort in commercial electronic design tools concentrates on logic and layout synthesis for semi-custom gate arrays, standard cell arrays and programmable arrays. Designs done this way are highly modifiable, and can be done by small teams. But they suffer performance penalties due to the use of restricted forms of circuits and layout. In high-performance design, where wire and gate delay must be accounted for in every block of logic and memory, these tools remove too much control from the designer and are fundamentally inadequate.

At the other extreme of the design spectrum are the full-custom tools used by an ever smaller number of design teams. These tools are built around layout as a master representation, and the layout editor as the main design tool. Such designs allow complete control over all aspects of performance. Unfortunately, layout is a very rigid representation that is difficult to modify. This leads to inflexible design methodologies in which functional partitions, interfaces and floorplans are fixed too early in the design cycle. This design style is also very vulnerable to changes in the underlying technology.

Recursive layout generation bridges the gap between semi-custom and full-custom design. It requires no compromise on performance; the tools allow full control over circuit selection and layout, and all tools work at the device level, not the gate level. Recursive layout generation also produces modifiable designs. Large complicated designs are created once, but modified forever. This system allows early and continual floorplanning, global performance tuning, and tracking of technology changes.

Recursive layout has been reported before. Ayres [1] describes recursive layout of synthesized PLA's from a netlist described by a program. Barth *et. al.* [2] described the recursive composition of hand-drawn cells connected by a channel router. The system described here is novel in that it allows synthesized and hand-drawn layout to be combined easily and connected automatically by a router to produce layouts which are virtually indistinguishable from those made by hand.

The recursive layout system was designed in order to build high-performance ECL and BiCMOS microprocessors [9]. Although we shall give examples of ECL circuits, almost nothing in the layout generation system is specific to a particular VLSI technology. The full set of tools developed for our microprocessor project also includes a switch-level bipolar timing verifier based on ideas in [8], a switch-level bipolar simulator [10], electrical rules and noise margin checkers [16], and extensions to the *magic* layout editor [12].

2. The Annotated Hierarchical Netlist

There is no single best way to describe circuits and logic. For analog circuits such as RAMs, schematic drawings of interconnected transistors are the most concise specification. For control logic, Boolean equations allow easiest debugging. For a parameterized n-bit adder a program is the most flexible representation. Rather than attempting to mix several different forms of circuit description, we chose to use their greatest common divisor, the program, and to translate schematics and Boolean equations into programs. Programs are simultaneously the most expressive and most modifiable descriptions we know of. We cast as much as possible of the design

process as a problem in software development, and use all the standard programming tools to change and debug our design. Many of our CAD tools are in libraries which can be linked and run with the circuit design.

We explicitly decided *not* to develop a specific programming language for hardware description. Instead, we embedded our hardware descriptions in a common programming language, C++. This entails some syntactic inconvenience, since wires, nets and cells are not base types in the language, but this is a small price to pay for extensibility. We were able to extend and change the hardware description language over the course of our project to add code for special purposes easily, without having to undertake language and compiler changes. We were able to debug our programs using standard tools. These advantages are compelling, and far outweigh syntactic convenience of a specialized but inflexible language.

The use of C++ led us naturally to another choice. A netlist is not a file, nor a database. It is a data structure in the virtual memory of a running program, the result of executing the cell generation code. Netlists for circuits with millions of devices can be generated in one or two minutes. This is probably faster than they can be read from a file. This model sidesteps the problems of versions of netlist files and consistent updates to databases which arise with other approaches. Our netlists are never saved, but generated as needed. Our source is a program composed of many files, and we maintain versions of them with standard revision control software.

2.1. Cell Generators

A circuit in our system is represented by a C++ program. A procedure in this program is a *cell generator*. It can take arbitrary parameters, and returns the netlist - a pointer to a C++ object called a *Cell* - for the requested cell. Many such generators take simple parameters, such as the amount of current drive to provide in the outputs, or the number of bits in a register, but some are quite complicated. For example, instead of having a library of OR-gates, we have an OR-gate generator, to which we pass the number of inputs, and a description of the outputs required. At this level, our form of description is quite like other hardware description languages. But our netlist fulfills one other function - it is designed to capture *all* the information needed to generate layout.

For circuits which are best described graphically, we use a conventional drawing editor for schematic capture.¹ The editor has no specialized knowledge of schematics, just as text editors have no knowledge of programs. These schematics drawings are "compiled" into C++ by our drawing interpreter *drip*, which interprets lines as wires, and names as labels of wires and devices. It uses only visible cues in the drawing to parse it into devices and wires, and can put arbitrary code, such as loops and tests, into the generated procedure. The resulting procedure is the equivalent structural description of interconnected devices. Two examples of schematics are shown in figure 1. These two cells carry annotations for layout which will cause them to be laid out by the *Leaf* cell synthesizer described below.

¹Note to reviewers: if the companion paper on *drip* is accepted for the conference, this section will be simplified and figure 1 deleted.

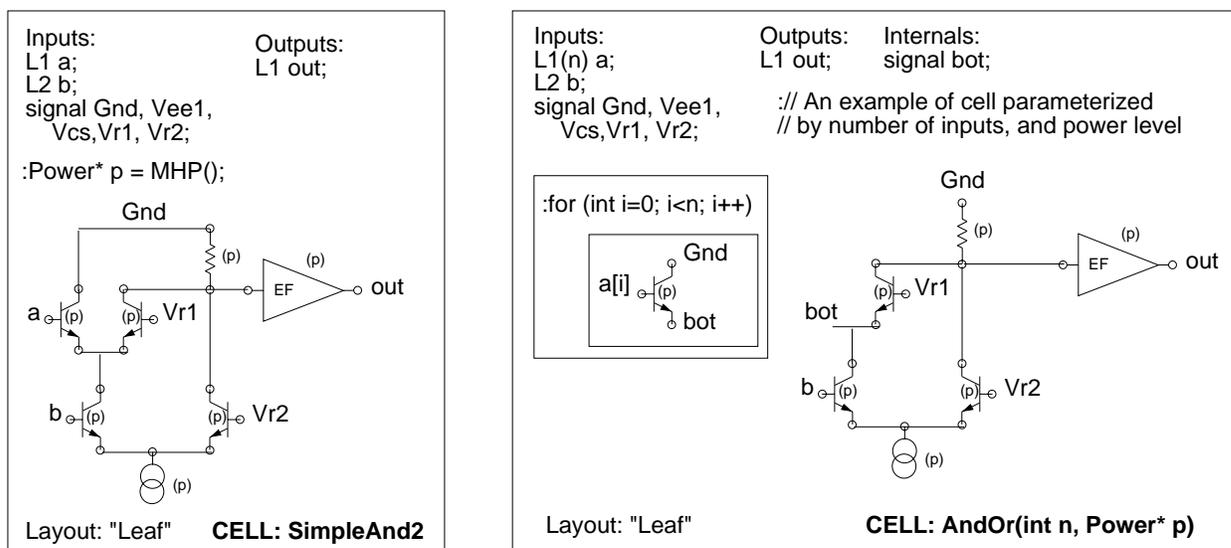


Figure 1: Cell schematics

```

1  Cell* Register(int n, Power* p) {
2      char key[100];
3      sprintf(key, "Register_%d_%s", n, p->name);
4      CACHECELL;
5      INW(clock, L3DPair());
6      INW(select, L2(1));
7      INW(in, L1(n));
8      OUTW(out, L1(n));
9      POWER;
10     for (int i=0; i<n; i++) {
11         INST(MuxFFCell("T2", "T", "T", p));
12         BD(i, in->Sub(i));
13         BD(s, select);
14         BD(c, clock);
15         BD(o, out->Sub(i));
16     }
17     SLK(AbutUp);
18     ENDCELL

```

Figure 2: A Cell Generator

Most circuits are better described by programs rather than drawings. Programs are more concise than drawings and much easier to modify. Figure 2 shows an example of a cell generator for a register. This procedure was written by hand, but is very similar to the output of *drip* that would be generated from the equivalent schematic. Functions in capitals are C++ macros, provided for syntactic convenience. A cell is a self-contained block of logic with an interface of named wires. Wires have types, analogous to arrays and structures in C++. Lines 5-9 describe the cell's interface, consisting of inputs (INW), outputs (OUTW), and power supplies (POWER). *Clock*, for instance, is an input wire of type *differential-pair-at-ECL-level-3*, and is a structure with two single-wire subfields *true* and *complementary*. Lines 10-16 describe the contents of the cell in terms of instances of subcells, here all of the same type, a one-bit flip-flop with a multiplexer on its input. The parameters to *MuxFFCell* describe the number and logic levels of its inputs and outputs, and the desired current drive. Lines 12-15 define how the named wires *i*, *s*, *c*, *o* in the subcell instance are to be bound (BD) to wires in this cell; all bits get the same select and clock wires, but the *i*'th bit gets the *i*'th input and output wires.

The netlist distinguishes between a cell and an instance of the cell. Cells are shared, and there is one copy of each unique cell. There is one instance for each use of the cell. In the example of figure 2, only one *MuxFFCell* will be created, but there will be n instances of it. Cell sharing is provided by the programming convention in all cell generators shown on lines 3-4. Each cell generator computes a unique name for the required cell based on the procedure name and parameter values. If the netlist for this cell already exists in a global cell cache, it is returned immediately at line 4. Otherwise the generator constructs the netlist, and stores it in the cell cache at line 18 before returning it to the caller. On subsequent calls with identical parameters, the generator returns the cached netlist.

The advantages of a hierarchical netlist with shared cells are enormous, since all aspects of a cell which are common between its many instances are shared. For instance, there is exactly one RAM cell in the netlist, but thousands of instances of that cell. The RAM cell layout is generated only once, but is then instantiated in many places in the chip layout. Cell sharing speeds up layout generation by orders of magnitude.

The hierarchical netlist also carries *annotations*. Line 17 shows a *layout method*, the most important annotation for the purpose of layout generation. A layout method completely describes how the cell layout is to be generated. "SLK" means "set layout key" and *AbutUp* is a particularly simple example; it lays out the instances in a cell from bottom to top in a column. Simple layout methods like *AbutUp* are just the name of a C++ procedure, but more complex layout methods described below carry associated data. The layout method is an integral part of the definition of the cell, and is specified by the designer just like the wires defining the cell's interface. If the same circuit needs to be laid out in two different ways, it is described by a cell generator accepting the layout method as a parameter. Two different cells will result from calls supplying different layout method arguments. They will have identical netlists, but different names and different layouts.

```
EQNCELL(FPDivCtl)
  INPUT(ck, L3DPair());
  INPUT(assign, L1());
  INPUT(bsign, L1());
  OUTPUT(sign, L1());
  OUTPUT(start, L1());
  . . .
  start <= op["div"] & ~abort & allowOp;
  sign <= FF(ck, start, assign ^ bsign);
  . . .
  SetStdCellLayout(cell, 3500, 250);
ENDEQNCELL
```

Figure 3: Boolean Equations

Another library of C++ functions provides the syntax of Boolean equations, which are extensively used for control logic and for prototyping new blocks of logic. Figure 3 shows a small example, whose layout is defined as a block of "standard cells" 3500 units wide with 250 units of vertical space between each row. The library maps these equations into valid ECL gates (such as n -input OR gates) during netlist generation. It makes use of three-level series gating, free inversion, and wired-OR [6]. The result of calling a cell generator defined by Boolean equations is a netlist identical to that which would be obtained by explicitly interconnecting a collection of gates, flip-flops and multiplexors. We trust the equation mapper to make this translation on parts of the circuit where precise selection of the gates used is not critical.

To generate a netlist for an entire chip, we translate all schematics into C++. The C++ source code for schematics, equations and hand-written cells is then compiled and linked with the CAD libraries. We also include a short main program which calls the generator for the top-level cell of the chip. A complete microprocessor having 4 million devices was described in 25K lines of C++; 15K lines of CAD libraries were linked with the design, resulting in a 10MB executable. The chip netlist was generated in a couple of minutes.

2.2. Netlist Traversal

When the main program calls the generator for the top-level cell in the circuit, it gets in return the annotated netlist for the circuit. This netlist can then be traversed to produce input files for simulators. We use SPICE for circuit simulation of analog circuits, and *bisim* [10] for switch-level simulation of digital circuits. Each simulator requires its own input file format, so there is a different traversal of the circuit netlist for each simulator. Writing the input file for a simulator takes about as long as initial generation of the netlist.

3. Layout Generation

Layout generation is best seen as just another traversal of the in-memory netlist. It is a bottom-up, batch process. No manual intervention is required, since all the information needed to generate the layout is in the netlist and in the layout methods. Layout happens in the same way for all cells. First, the subcells are laid out recursively. Then the cell's layout method is used to place the instances of the subcells. After placement, some connections may have been made by abutment or overlap. Any which remain are completed by the *Contour* router [4]. Finally, connectivity checks are made to detect shorts and opens. An electrical short of two nets is usually a sign of overlapping subcells in an incorrect placement. Opens usually result from creating a routing problem which is too difficult. Both of these problems are solved by editing the layout method for the cell, and *never ever* by editing the generated layout directly. In this way we maintain the rule that all information needed to generate the entire layout is recorded on the netlist.

The representation of layout for a cell comes in two parts. The geometry of the instances of the subcells is defined simply by the transformations of the subcell layout which place them in the current cell. New rectangles defined in the layout of this cell - for example the wires and vias added by the router - are stored in a set of tiling planes [14], one per layer in the VLSI technology (usually one for each metal layer, and one for the active devices). Layout generation is correct by construction - unless shorts and opens are detected and reported - and two invariants are maintained for every cell:

- The layout represents the same circuit as the netlist. There are the same number of devices of the same sizes, interconnected in the same way.
- The cell geometry in the tiling planes is maintained in an extracted form; each solid tile is labelled with the net to which it belongs.

3.1. Hand-Drawn Cells

The recursion ends at hand-drawn cells, which do not depend on layout of the subcells. These cells have the layout method *ReadMagic*, and laying them out means reading a file of the same name made with the *magic* layout editor. The use of a hand-drawn cell comes at a price; its layout must be manually maintained over all future changes in technology or in pitch-matching to other cells. Our system is no better at managing large tracts of hand layout than any other, so hand-drawn cells are used either for analog cells such as pads, or for memory cells, where the gain in density is compelling. Figure 4 shows the layout of two bits of register file.

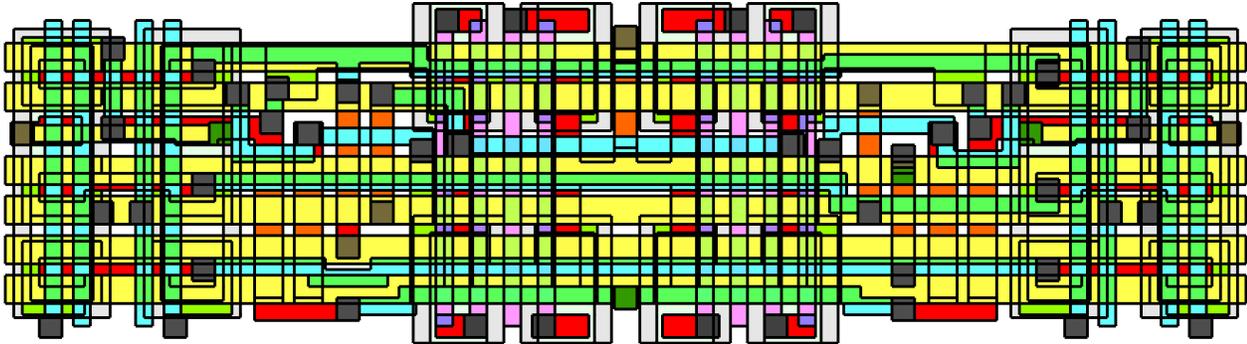


Figure 4: A hand-drawn cell

The result of reading the *magic* file for the cell is a set of tiling planes full of rectangles. Hand-drawn cells have no instances of subcells, so the entire geometry of the cell is represented in the tiling planes. But the two layout invariants must be checked; the layout must represent the same circuit as the netlist, and each rectangle has to be associated with its net in the netlist. First the netlist represented by the layout is extracted by finding the transistors and resistors, and following their interconnections. Then this netlist is matched with the netlist specified for the cell by a graph isomorphism method similar to *gemini* [5]. The matching is purely topological, though labels in the hand layout can be used to disambiguate symmetries. If the graphs are identical, each rectangle can be labelled with the correct net, and the layout has been proved to match the netlist. In case of mismatch, an error is immediately reported.

Hand-drawn cells are also routed just like any other cell, since the extracted layout makes it clear which nets are disconnected. Our router is able to make connections to arbitrary geometry and route in obstructed areas, and the designer may choose to leave some of the wiring to the router even in hand-drawn cells. A good example of this is a 64-bit decoder which has a 6-bit input bus, in which it is extremely easy to make a wiring error. In this case, labelling the device terminals and bus wires is less error-prone than wiring by hand.

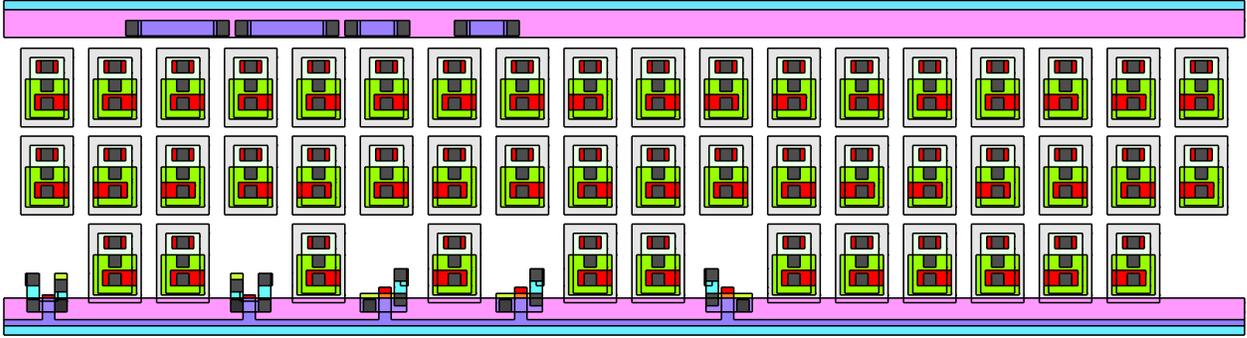


Figure 5: A leaf cell after placement

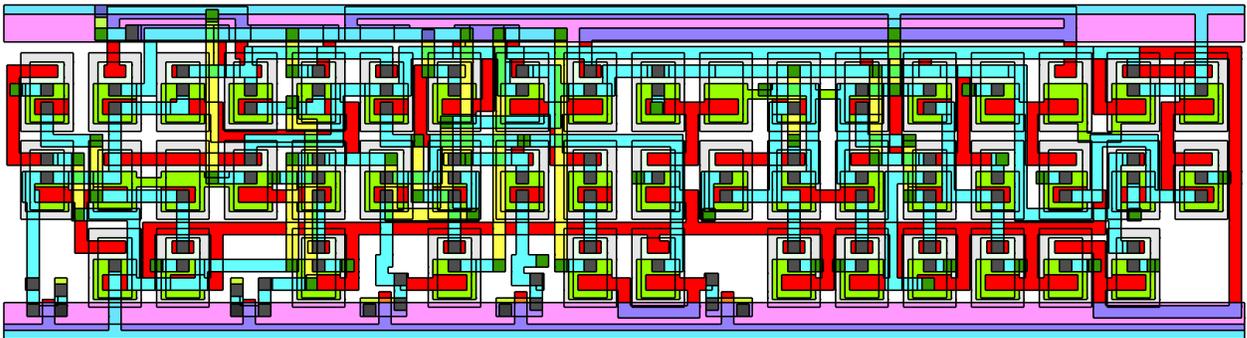


Figure 6: The same leaf cell after routing

3.2. Leaf Cells

Many small cells are synthesized using the *Leaf* layout method. Typically, these are gate-level cells, containing up to a hundred transistors. Figure 5 shows a flip-flop with a 10-input integrated multiplexor after placement by *Leaf*. Figure 6 shows the same cell with the wiring added by *Contour*.

Leaf is a general ECL cell synthesizer. It produces finished layout given the netlist of devices, the layouts for the devices (they all have the *ReadMagic* layout method), and a vertical pitch. This synthesizer is one of the few parts of the layout system dependent on ECL technology. The placement uses no hints from the designer, but selects positions of the transistors and resistors which maximize the number of connections which can be made using polysilicon interconnect. The resulting placement is very close to the density of hand designs. In part this is due to the regularity of current trees in ECL logic and the similar sizes of bipolar devices. The current algorithm - the sixth and by far the best in the history of the project - is based on exhaustive combinatorial search. It finds very good placements in milliseconds. The key ideas are to consider the transistors in the right order (by current tree, then by closeness to the current source within each current tree), and to avoid the use of a cost function to compare a large number placements. In place of a cost function, the algorithm has a *rejection criterion* and an *acceptance criterion*. The rejection criterion is used to prune the search tree by detecting partial placements which can never lead to a good complete placement, perhaps because a current tree can not be placed contiguously. The *acceptance criterion* is a strict definition of a good placement. The first complete placement passing the criterion is accepted as the final solution.

After placement, routing of leaf cells is done by our *Contour* router in polysilicon and up to three levels of metal. Routing in second- and third-level metal is permitted but discouraged by the cost parameters given to *Contour*. Complete layout generation for a typical leaf cell takes from 1 to 50 seconds on a DECStation 5000/200.

This style of leaf cell synthesis may be contrasted with semi-custom design. In our system there is no cell library, and we cannot predict in advance which 2000 or so of the enormous number of legal ECL gates will actually be used. The particular gate selection is determined by the parameters passed to the gate generator procedures during creation of the netlist. Each distinct gate is made exactly once - because of the sharing enforced by the cell cache during netlist generation - and is instantiated one or more times. During layout generation therefore, each unique ECL gate is placed and routed exactly once, and that layout is shared among all its instances.

3.3. Composite Cells

Most higher-level cells are neither hand-drawn nor synthesized, and a variety of layout methods are used for them. For completely regular cells such as multi-bit registers, simple layout methods like *AbutUp* and *AbutRight* are used to arrange the subcells in rows or columns. For completely random cells, such as blocks of control logic, *StdCell*, a fully automatic placer based on the conjugate gradient method [11] generates rectangular blocks with minimal wire distance. For cells which are neither fully random, nor fully regular, a layout method based on corner and edge alignment is used to place subcells to the last micron.

```

1 // four RAM cells in a symmetrical 2x2 square
2 CELL(RamQuad)
3   INW(wwl0, oneBit());   INW(wwl1, oneBit());
4   INW(rwl0, oneBit());   INW(rwl1, oneBit());
5   OUTW(rbl0, DiffPair()); OUTW(rbl1, DiffPair());
6   OUTW(wbl0, DiffPair()); OUTW(wbl1, DiffPair());
7   POWER;
8   AlignRegion quad("quad");
9
10  INST(RamBit());
11  BD(rwl, rwl0); BD(wwl, wwl0); BD(rbl, rbl0); BD(wbl, wbl0);
12  InstRegion bit0(instance); /* lower left */
13
14  INST(RamBit());
15  BD(rwl, rwl0); BD(wwl, wwl0); BD(rbl, rbl1); BD(wbl, wbl1);
16  InstRegion bit1(instance, TopToBottom);
17  quad.Align(bit1, LL, bit0, UL); /* upper left */
18
19  INST(RamBit());
20  BD(rwl, rwl1); BD(wwl, wwl1); BD(rbl, rbl0); BD(wbl, wbl0);
21  InstRegion bit2(instance, RightToLeft);
22  quad.Align(bit2, LL, bit0, LR); /* lower right */
23
24  INST(RamBit());
25  BD(rwl, rwl1); BD(wwl, wwl1); BD(rbl, rbl1); BD(wbl, wbl1);
26  InstRegion bit3(instance, Rotate180);
27  quad.Align(bit3, LL, bit0, UR); /* upper right */
28
29  SetLayout(cell, quad);
30 ENDCELL

```

Figure 7: Layout by Corner Alignment

Figure 7 shows how corner alignment is used to assemble four RAM cells into a 2x2 array which is symmetrical around both the horizontal and vertical center lines. This cell is the repeating unit of four bits in a cache RAM. Here, an *AlignRegion* object is declared at line 8, and corner alignments are added to it at lines 15, 19 and 23. In line 24, the resulting data structure is made the layout method of the cell. The instructions for generating the layout (lines 14-15: "flip bit1 top to bottom, then align its lower left corner to the upper left of bit0") are simply recorded as annotations on the cell during netlist generation. When layout is required for this cell, the alignments are retrieved and executed.

Note that layout by corner and edge alignment is independent of the size of the underlying *RamBit* cell. This is important; editing the hand-drawn *RamBit* cell will not invalidate this layout. We contrast this with normal hand assembly of layout, in which the series of keystrokes and mouse clicks to arrange the subcells is lost. If the *RamBit* changes size, these keystrokes and mouse clicks must be repeated manually. With recursive layout generation, only a program needs to be re-executed.

Integrating corner alignment directives with the netlist has proved very successful. It might be objected that the layout directives obscure the connectivity of the netlist, but in practice this has not been a problem. Having all the information about a cell in one place makes circuit modifications much easier. Whenever a cell's netlist needs to be changed, it is usually quite easy to make the corresponding layout changes, especially when the reward of a new color plot can be generated quickly.

3.4. Routing

A large fraction of the development effort was spent on *Contour*, a general router based on a hybrid maze/line search principles [3, 13, 7] and the corner-stitched data structure [14, 15]. *Contour* is used in each cell of the design to complete connections not made by placement. In general, the router is adding wires to cells on top of wires already routed in the subcells. Routing over the top of active logic is one of the characteristics of custom VLSI, and is largely responsible for its density. For this reason conventional channel routers, which route only over unobstructed rectangular channels, are unacceptable. *Contour* reads design rules from the same file used by the design-rule checker. It can generate routing with minimum dimensions and clearances from obstacles on all wiring layers simultaneously. *Contour* is used repeatedly at all levels of the design, from routing polysilicon in the leaf cells to chip assembly. In fact, part of a layout method is a set of directions to the router on the correct use of metal and/or polysilicon layers to connect the nets.

Routing a cell is done by breaking each net into a spanning tree of pairwise *connections* between disconnected *terminals*. Terminals are not simple rectangular connection points, but arbitrary collections of wires and devices - in general they are the result of previous routing in subcells. These connections are then ordered by likely difficulty in order to produce a connection schedule for the cell. The connections are then attempted in order of increasing difficulty. Each connection is completed by finding a design-rule-correct path between its terminals. If a path can be found, the next connection is attempted. In case of blockage, previously made connections are removed and re-routed later.

Contour uses a breadth-first routing algorithm based on a single principle; *postpone arbitrary choices*. When such choices arise, such as "should the connection start with a wire or a via?", or "should we turn left or right around this obstacle?", *all* the alternatives are explicitly represented, maintained and propagated until there is enough information to discriminate between them. During early attempts to implement the router, we did not rigorously adhere to this principle, believing it to be too complicated or too costly to implement. The result was always a router that would surprise us by the paths it had chosen for some connections ("Why did it do *that*?"). Only when we finally eliminated all arbitrary choices in the algorithm did the router choose exactly the paths a person would.

3.5. Netlist Hierarchy Equals Layout Hierarchy?

Is the hierarchy described by the annotated netlist strictly the same as the hierarchy of the cells which are laid out? Yes, but with a single exception. The layout method for any cell may choose to flatten the netlist for its cell selectively. For the purposes of layout only, intermediate cells of netlist may be exploded, and their instances promoted to be instances of the top-level cell. Two uses of this flattening are in the layout methods *StdCell* and *ReadMagic*. *StdCell*, the "standard-cell" layout method for random logic, removes some, but not all layers of its cell's hierarchy. It flattens the netlist until it contains only gate-level instances. So for instance, a 10-bit register would be considered as ten independent bit layouts by *StdCell*. *ReadMagic* flattens its cell completely until it contains only bare devices; all intervening cells in the hierarchy are ignored for this purpose. This flattened netlist can then be matched against the extracted hand-drawn layout. Allowing *ReadMagic* to be used for complex cells is a kind of escape mechanism from the failure of our automatic placement and routing; when all else fails, draw it by hand. We have never used it this way to date.

Even though the netlist and layout hierarchies must be similar, we do not believe that this results in an unnatural logical partitioning of circuits. In general, a piece of logic is defined as a cell in our system whenever one or more of the following conditions holds:

- *logical*: the number of wires in the cell's interface is much smaller than the number of wires used to connect the instances of its subcells.
- *sharing*: there will be many instances of this cell in the circuit.
- *layout*: the cell represents a natural unit of layout.
- *simulation*: the cell carries a functional model for some level of simulation.

Very often, these conditions occur naturally together. A frequently used piece of logic with a small interface is likely to be a natural unit of layout. When these conditions are kept in mind at the start of a design, a netlist fulfilling the requirements of layout and simulation can be built just as easily as any other. Imposing these conditions after the fact can be painful.

4. Results

Figure 8 shows the floating-point divider from BIPS-1, a 4,000,000-device BiCMOS microprocessor. The divider contains 20,000 transistors, and occupies about 5% of the chip area. It consists of 118 unique cells, 97 of which are synthesized leaf cells, and 21 of which are composite cells such as 64-bit registers or blocks of control logic. The large block on the left and center is the mantissa data path. It consists of multiplexors and registers laid out by abutment (the long dark horizontal bands) and three carry-lookahead adders assembled by corner alignment (the areas with irregular lower borders are the carry-lookahead trees). The exponent data path, with one smaller adder, is on the upper right. The sequencer is the irregular block on the lower right, laid out by *StdCell*. Assembly of the top-level cell was by corner alignment. The divider was designed, simulated, laid out, and tuned for performance by two people in two months, and survived several design-rule changes without further modification. Layout of the divider takes 10 minutes on a DEC 3000/800 Alpha workstation.

Recursive layout generation has permitted a small team to design large chips. It was used to construct BIPS-0, a bipolar processor [9], shown in figure 9. The entire design team for this chip was twelve people, including two mechanical engineers and three people working entirely on CAD. The layout generation of this complete 700,000-device circuit took ten hours with no manual intervention. This allowed one complete iteration of the design per day.

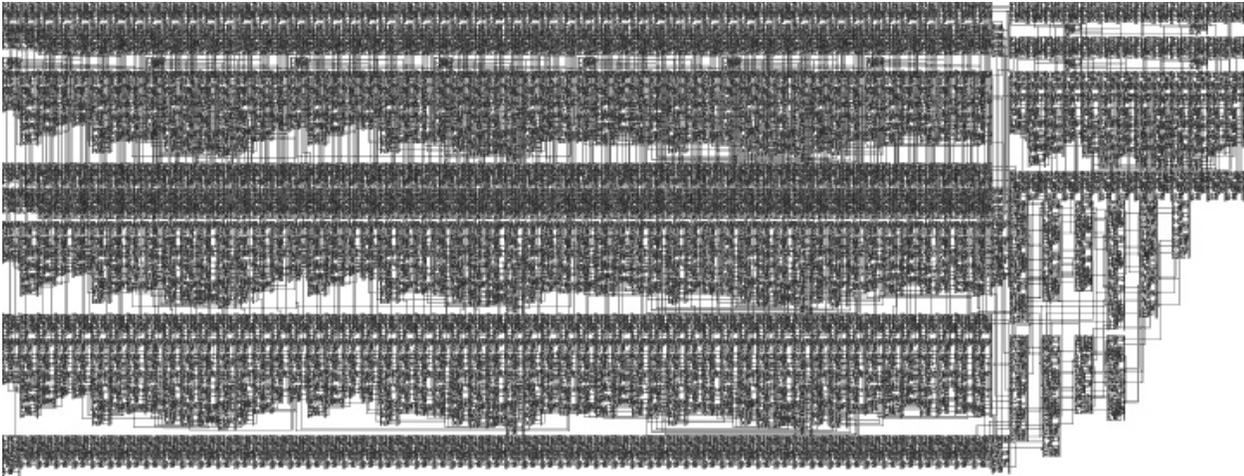


Figure 8: The BIPS-1 64-bit Floating-Point Divider

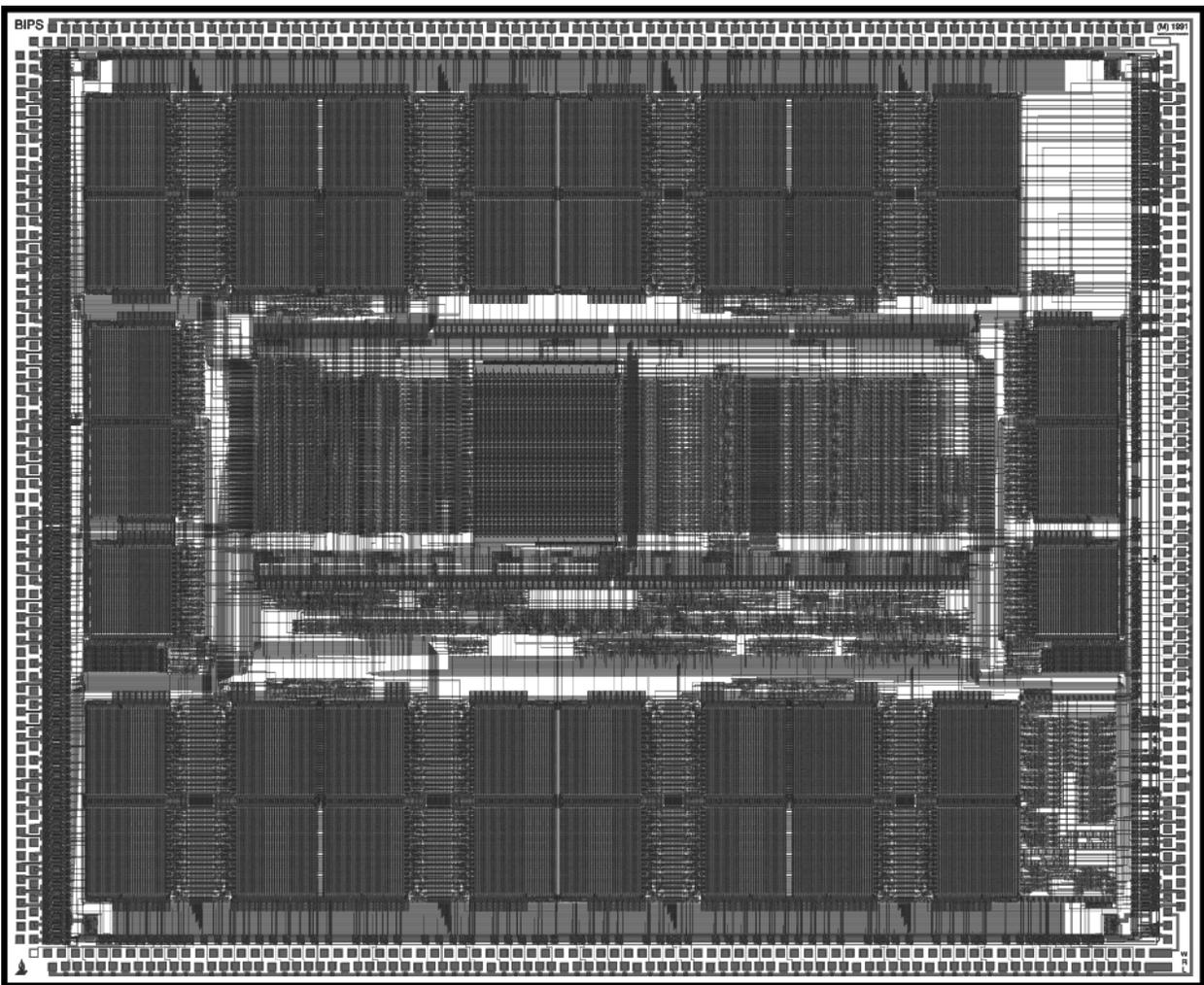


Figure 9: The BIPS-0 Microprocessor

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