

University of California at Berkeley
College of Engineering
Department of Electrical Engineering and Computer Science

EECS 151/251A, Fall 2020

Project Specification

EECS 151/251A RISC-V Processor Design

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1 Introduction

The primary goal of this project is to familiarize students with the methods and tools of digital design. In order to make the project both interesting and useful, we will guide you through the implementation of a CPU that is intended to be integrated on a modern SoC. Working alone or in teams of 2, you will be designing a simple 3-stage CPU that implements the RISC-V ISA, developed here at UC Berkeley. If you work in a team, you both must work on the project together (i.e. you are not allowed to divide up the work), and you will both receive the same grade.

Your first and most important goal is to write a functional implementation of your processor. To better expose you to real design decisions, you will also be tasked with improving the performance of your processor. You will be required to meet a minimum performance to be specified later in the project.

You will use Verilog HDL to implement this system. You will be provided with some testbenches to verify your design, but you will be responsible for creating additional testbenches to exercise your entire design. Your target implementation technology will be the ASAP7 7nm Educational PDK, a predictive model technology used for instruction. The project will give you experience designing synthesizable RTL (Register Transfer Level) code, resolving hazards in a simple pipeline, building interfaces, and approaching system-level optimization.

Your first step will be to map our high level specification to a design which can be translated into a hardware implementation. You will then generate and debug that implementation in Verilog. These steps may take significant time if you do not put effort into your system architecture before attempting implementation. After you have built a working design, you will be optimizing it for speed in the 7nm technology that we have been using this semester.

1.1 RISC-V

The final project for this class will be a VLSI implementation of a RISC-V (pronounced *risk-five*) CPU. RISC-V is an instruction set architecture (ISA) developed here at UC Berkeley. It was originally developed for computer architecture research and education purposes, but recently there has been a push towards commercialization and industry adoption. For the purposes of this lab, you don't need to delve too deeply into the details of RISC-V. However, it may be good to familiarize yourself with it, as this will be at the core of your final project. Check out the official [Instruction Set Manual](#) and explore <http://riscv.org> for more information.

- Read through sections 2.2 and 2.3 in the [RISC-V Instruction Set Manual](#) to understand how the different types of instructions are encoded. Most of this should be familiar as it is similar to MIPS.
- Read through sections 2.4, 2.5, and 2.6 in the Instruction Set Manual and think about how each of the instructions will use the ALU.

You do not need to read 2.7 or 2.8, as you will not be implementing those instructions in the project.

1.2 Project phases

Your project will consist of two different phases: front-end and back-end. Within each phase, you will have multiple checkpoints that will ensure you are making consistent progress. These checkpoints will

contribute (although not significantly) to your final grade. You are free to make design changes after they have been checked off if they will help subsequent phases or improve QoR.

In the first phase (front-end), you will design and implement a 3-stage RISC-V processor in Verilog, and run simulations to test for functionality. At this point, you will only have a functional description of your processor that is independent of technology (there are no standard cells yet). You have about 5 weeks to complete the first phase, but you are highly encouraged to try to finish each checkpoint early, as each checkpoint will be released before the due date of the ongoing one. Everything will take much longer than you expect, and finishing early gives you more time to improve your QoR (Quality of Results, e.g. clock period).

In the second phase (back-end), you will implement your front-end design in the ASAP7 7nm kit using the VLSI tools you used in lab. When you have finished phase 2, you will have a design that could move onto fabrication if this were a real process. You will have about 2 weeks to complete the second phase after its release.

1.3 Philosophy

This document is meant to describe a high-level specification for the project and its associated support hardware. You can also use it to help lay out a plan for completing the project. As with any design you will encounter in the professional world, we are merely providing a framework within which your project must fit.

You should consider the GSI(s) a source of direction and clarification, but it is up to you to produce a fully functional design, as well as a physical implementation. I/We will attempt to help, when possible, but ultimately the burden of designing and debugging your solution lies on you.

1.4 General Project Tips

Be sure to use top-down design methodologies in this project. We began by taking the problem of designing a basic computer system, modularizing it into distinct parts, and then refining those parts into manageable checkpoints. You should take this scheme one step further; we have given you each checkpoint, so break each into smaller, manageable pieces.

As with many engineering disciplines, digital design has a normal development cycle. In the norm, after modularizing your design, your strategy should roughly resemble the following steps:

Design your modules well, make sure you understand what you want before you begin to code.

Code exactly what you designed; do not try to add features without redesigning.

Simulate thoroughly; writing a good testbench is as much a part of creating a module as actually coding it.

Debug completely; *anything which can go wrong with your implementation will.*

Document your project thoroughly as you go. Your design review documents will help, but you should never forget to comment your Verilog and to keep your diagrams up to date. Aside from the final project report (you will need to turn in a report documenting your project), you can use your design documents to help the debugging process. Finish the required features first. Attempt extra features after everything works well.

This project is divided into checkpoints. Each checkpoint will be due 1 to 2 weeks after its release, but the next checkpoint will be released early. Use this to your advantage- try to get ahead so that you have additional time to debug. Your TA will clarify the specific timeline for your semester.

The most important goal is to design a functional processor- this alone is 50-60% of the final grade, and you must have it **working completely** to receive *any* credit for performance.

2 Front-end design (Phase 1)

The first phase in this project is designed to guide the development of a three-stage pipelined RISC-V CPU that will be used as a base system for your back-end implementation.

Phase 1 will last for 5 weeks and has weekly checkpoints.

- Checkpoint 1: ALU design and pipeline diagram (due Thursday, November 5, 2020)
- Checkpoint 2: Core implementation (due Wednesday, November 18, 2020)
- Checkpoint 3: Core + memory system implementation (due Wednesday, November 25, 2020)

2.1 Project Setup

The skeleton files for the project will be delivered as a git repository provided by the staff. You should clone this repository as follows. It is highly recommended to familiarize yourself with git and use it to manage your development.

```
% git clone /home/ff/eecs151/labs/project_skeleton /path/to/my/project
```

To get a team repo, fill out the google form via the link on Piazza with your team information. Please do this even if you are working alone, as these git repos will be used for part of the final checkoff. Once it is setup you will be given a team number, and you will be given a repo hosted on the servers for version control for the project. You should be able to add the remote host of “geecs151:teamXX” where “XX” is the team number that you are assigned. An example working flow to be able to pull from the skeleton as well as push/pull with your team repository is shown below:

```
% git clone /home/ff/eecs151/labs/project_skeleton /path/to/my/project
% git remote add myOrigin geecs151:teamXX
```

Then to pull changes from the skeleton, you would need to type:

```
% git pull origin master
```

To pull changes from your team repository you would type:

```
% git pull myOrigin master
```

And to push changes to your team repository (please do not attempt to push to the skeleton repository), you would usually want to pull first (above) and then type:

```
% git push myOrigin master
```

3 Checkpoint #1: ALU design and pipeline diagram

The ALU that we will implement in this lab is for a RISC-V instruction set architecture. Pay close attention to the design patterns and how the ALU is intended to function in the context of the RISC-V processor. In particular it is important to note the separation of the datapath and control used in this system which we will explore more here.

The specific instructions that your ALU must support are shown in the tables below. The branch condition should **not** be calculated in the ALU. Depending on your CPU implementation, your ALU may or may not need to do anything for branch, jump, load, and store instructions (i.e., it can just output 0).

3.1 Making a pipeline diagram

The first step in this project is to make a pipeline diagram of your processor, as described in lecture. You only need to make a diagram of the datapath (not the control). Each stage should be clearly separated with a vertical line, and flip-flops will form the boundary between stages. It is a good idea to name signals depend on what stage they are in (eg. `s1_killf`, `s2_rd0`). Also, it is a good idea to separately name the input/output (D/Q) of a flip flop (eg. `s0_next_pc`, `s1_pc`). Draw your diagram in a drawing program (Inkscape, Google Drawings, draw.io or any program you want), because you will need to keep it up-to-date as you build your processor. It helps to print out scratch copies while you are debugging your processor and to keep your drawings revision-controlled with git. Once you have finished your initial datapath design, you will implement the main building block in the datapath—the ALU.

3.2 ALU functional specification

Given specifications about what the ALU should do, you will create an ALU in Verilog and write a test harness to test the ALU.

The encoding of each instruction is shown in the table below. There is a detailed functional description of each of the instructions in Section 2.4 (starting on page 13) of the [Instruction Set Manual](#). Pay close attention to the functional description of each instruction as there are some subtleties. Also, note that the `LUI` instruction is somewhat different from the MIPS version of `LUI` which some of you may be used to.

31	27	26	25	24	20	19	15	14	12	11	7	6	0	
funct7				rs2		rs1		funct3		rd		opcode		R-type
imm[11:0]						rs1		funct3		rd		opcode		I-type
imm[11:5]				rs2		rs1		funct3		imm[4:0]		opcode		S-type
imm[12 10:5]				rs2		rs1		funct3		imm[4:1 11]		opcode		SB-type
imm[31:12]										rd		opcode		U-type
imm[20 10:1 11 19:12]										rd		opcode		UJ-type

RV32I Base Instruction Set

imm[31:12]				rd		0110111		LUI rd,imm
imm[31:12]				rd		0010111		AUIPC rd,imm
imm[20 10:1 11 19:12]				rd		1101111		JAL rd,imm
imm[11:0]				rs1		000		JALR rd,rs1,imm
imm[12 10:5]		rs2		rs1		000		BEQ rs1,rs2,imm
imm[12 10:5]		rs2		rs1		001		BNE rs1,rs2,imm
imm[12 10:5]		rs2		rs1		100		BLT rs1,rs2,imm
imm[12 10:5]		rs2		rs1		101		BGE rs1,rs2,imm
imm[12 10:5]		rs2		rs1		110		BLTU rs1,rs2,imm
imm[12 10:5]		rs2		rs1		111		BGEU rs1,rs2,imm
imm[11:0]				rs1		000		LB rd,rs1,imm
imm[11:0]				rs1		001		LH rd,rs1,imm
imm[11:0]				rs1		010		LW rd,rs1,imm
imm[11:0]				rs1		100		LBU rd,rs1,imm
imm[11:0]				rs1		101		LHU rd,rs1,imm
imm[11:5]		rs2		rs1		000		SB rs1,rs2,imm
imm[11:5]		rs2		rs1		001		SH rs1,rs2,imm
imm[11:5]		rs2		rs1		010		SW rs1,rs2,imm
imm[11:0]				rs1		000		ADDI rd,rs1,imm
imm[11:0]				rs1		010		SLTI rd,rs1,imm
imm[11:0]				rs1		011		SLTIU rd,rs1,imm
imm[11:0]				rs1		100		XORI rd,rs1,imm
imm[11:0]				rs1		110		ORI rd,rs1,imm
imm[11:0]				rs1		111		ANDI rd,rs1,imm
0000000		shamt		rs1		001		SLLI rd,rs1,shamt
0000000		shamt		rs1		101		SRLI rd,rs1,shamt
0100000		shamt		rs1		101		SRAI rd,rs1,shamt
0000000		rs2		rs1		000		ADD rd,rs1,rs2
0100000		rs2		rs1		000		SUB rd,rs1,rs2
0000000		rs2		rs1		001		SLL rd,rs1,rs2
0000000		rs2		rs1		010		SLT rd,rs1,rs2
0000000		rs2		rs1		011		SLTU rd,rs1,rs2
0000000		rs2		rs1		100		XOR rd,rs1,rs2
0000000		rs2		rs1		101		SRL rd,rs1,rs2
0100000		rs2		rs1		101		SRA rd,rs1,rs2
0000000		rs2		rs1		110		OR rd,rs1,rs2
0000000		rs2		rs1		111		AND rd,rs1,rs2
imm[11:0]				rs1		001		CSRRW rd,rs1,imm
imm[11:0]				rs1		101		CSRRWI rd,rs1,imm

3.3 Project Files

We have provided a skeleton directory structure to help you get started.

Inside, you should see a `src` folder, as well as a `tests` folder. The `src` folder contains all of the verilog modules for this phase, and the `tests` folder contains some RISC-V test binaries for your processor.

3.4 Testing the Design

Before writing any of modules, you will first write the tests so that once you've written the modules you'll be able to test them immediately. This is effectively Test-driven Development (TDD). Writing tests first is good practice- it forces you to write thorough tests, and ensures that tests will exist when you need to rapidly iterate through module design tweaks. Thorough understanding of the expected functionality is key to writing good tests (or RTL). You will be expected to write unit tests for any modules that you design and implement and write integration tests. Unit tests will verify the functionality of individual modules against your specification. Integration tests verify that all the modules work as a system once you connect them together.

3.4.1 Verilog Testbench

One way of testing Verilog code is with testbench Verilog files. The outline of a test bench file has been provided for you in `ALUTestbench.v`. There are several key components to this file:

- ``timescale 1ns / 1ps` - This specifies, in order, the reference time unit and the precision. This example sets the unit delay in the simulation to 1ns (i.e. #1 = 1ns) and the precision to 1ps (i.e. the finest delay you can set is #0.001 = 1ps).
- The clock is generated by the code below. Since the ALU is only combinational logic, this is not necessary, but it will be a helpful reference once you have sequential elements.
 - The `initial` block sets the clock to 0 at the beginning of the simulation. You should be sure to only change your stimulus when the clock is falling, since the data is captured on the rising edge. Otherwise, it will not only be difficult to debug your design, but it will also cause hold time violations when you run gate level simulation.
 - You must use an `always` block without a sensitivity list (the `@` part of an `always` statement) to cause the clock to run automatically.

```
parameter Halfcycle = 5; //half period is 5ns
localparam Cycle = 2*Halfcycle;
reg Clock;
// Clock Signal generation:
initial Clock = 0;
always #(Halfcycle) Clock = ~Clock;
```

- `task checkOutput`; - this task contains Verilog code that you would otherwise have to copy paste many times. Note that it is **not** the same thing as a function (as Verilog also has functions).
- `{$random} & 31'h7FFFFFFF` - `$random` generates a pseudorandom 32-bit integer. A bitwise AND will mask the result for smaller bit widths.

For these two modules, the inputs and outputs that you care about are `opcode`, `funct`, `add_rshift_type`, `A`, `B` and `Out`. To test your design thoroughly, you should work through every possible `opcode`, `funct`, and `add_rshift_type` that you care about, and verify that the correct `Out` is generated from the `A` and `B` that you pass in.

The test bench generates random values for `A` and `B` and computes `REFout = A + B`. It also contains calls to `checkOutput` for load and store instructions, for which the ALU should perform addition. It will be up to you to write tests for the remaining combinations of `opcode`, `funct`, and `add_rshift_type` to test your other instructions.

Remember to restrict `A` and `B` to reasonable values (e.g. masking them, or making sure that they are not zero) if necessary to guarantee that a function is sufficiently tested. Please also write tests where the inputs and the output are hard-coded. These should be corner cases that you want to be certain are stressed during testing.

3.4.2 Test Vector Testbench

An alternative way of testing is to use a test vector, which is a series of bit arrays that map to the inputs and outputs of your module. The inputs can be all applied at once if you are testing a combinational logic block or applied over time for a sequential logic block (e.g. an FSM).

You will write a Verilog testbench that takes the parts of the bit array that correspond to the inputs of the module, feeds those to the module, and compares the output of the module with the output bits of the bit array. The bit vector should be formatted as follows:

```
[106:100] = opcode
[99:97] = funct
[96] = add_rshift_type
[95:64] = A
[63:32] = B
[31:0] = REFout
```

Open up the skeleton provided to you in `ALUTestVectorTestbench.v`. You need to complete the module by making use of `$readmemb` to read in the test vector file (named `testvectors.input`), writing some assign statements to assign the parts of the test vectors to registers, and writing a for loop to iterate over the test vectors.

The syntax for a for loop can be found in `ALUTestbench.v`. `$readmemb` takes as its arguments a filename and a reg vector, e.g.:

```
reg [5:0] bar [0:20];
$readmemb("\foo.input", bar);
```

3.4.3 Writing Test Vectors

Additionally, you will also have to generate actual test vectors to use in your test bench. A test vector can either be generated in Verilog (like how we generated `A`, `B` using the random number generator and iterated over the possible opcodes and functs), or using a scripting language like Python. Since we have already written a Verilog test bench for our ALU and decoder, we will tackle writing a few test vectors by hand, then use a script to generate test vectors more quickly.

Test vectors are of the format specified above, with the 7 `opcode` bits occupying the left-most bits. In the `tests` folder, create the file `testvectors.input` and add test vectors for the following instructions to the end (i.e. manually type the 107 zeros and ones required for each test vector): `SLT`, `SLTU`, `SRA`, and `SRL`.

In the same directory, we've also provided a test vector generator `ALUTestGen.py` written in Python, which is a popular language used for scripting. We used this generator to generate the test vectors provided to you. If you're curious, you can read the next paragraph and poke around in the file. If not, feel free to skip ahead to the next section.

The script `ALUTestGen.py` is located in `tests`. Run it so that it generates a test vector file in the `tests` folder. Keep in mind that this script makes a couple assumptions that aren't necessary and may differ from your implementation:

- Jump, branch, load and store instructions will use the ALU to compute the target address.
- For all shift instructions, A is shifted by B. In other words, B is the shift amount.
- For the LUI instruction, the value to load into the register is fed in through the B input.

You can either match these assumptions or modify the script to fit with your implementation. All the methods to generate test vectors are located in the two Python dictionaries `opcodes` and `functs`. The lambda methods contained (separated by commas) are respectively: the function that the operation should perform, a function to restrict the A input to a particular range, and a function to restrict the B input to a particular range.

If you modify the Python script, run the generator to make new test vectors. This will overwrite the `testvectors.input` file, so if you want to save your handwritten test vectors, rename the file before running the script, then append them once the file has been generated.

```
% python ALUTestGen.py
```

This will write the test vector into the file `testvectors.input`. Use this file as the target test vector file when loading the test vectors with `$readmemb`.

3.5 Writing Verilog Modules

For this exercise, we've provided the module interfaces for you. They are logically divided into a control (`ALUdec.v`) and a datapath (`ALU.v`). The datapath contains the functional units while control contains the necessary logic to drive the datapath. You will be responsible for implementing these two modules. Descriptions of the inputs and outputs of the modules can be found in the first few lines of each file. The ALU should take an `ALUop` and its two inputs A and B, and provide an output dependent on the `ALUop`. The operations that it needs to support are outlined in the Functional Specification. Don't worry about sign extensions—they should take place outside of the ALU. The ALU decoder uses the `opcode`, `funct`, and `add_rshift_type` to determine the `ALUop` that the ALU should execute. The `funct` input corresponds to the `funct3` field from the ISA encoding table. The `add_rshift_type` input is used to distinguish between `ADD/SUB`, `SRA/SRL`, and `SRAI/SRLI`; you will notice that each of these pairs has the same `opcode` and `funct3`, but differ in the `funct7` field.

You will find the case statement useful, which has the following syntax:

```

always@(*) begin
    case(foo)
        3'b000: // something happens here
        3'b001: // something else happens here
        3'b010, 3'b011: // you can have more than
                        // one case do the same thing
        default: // everything else
    endcase
end

```

To make your job easier, we have provided two Verilog header files: `Opcode.vh` and `ALUop.vh`. They provide, respectively, macros for the opcodes and functs in the ISA and macros for the different ALU operations. You should feel free to change `ALUop.vh` to optimize the `ALUop` encoding, but if you change `Opcode.vh`, you will break the test bench skeleton provided to you. You can use these macros by placing a backtick in front of the macro name, e.g.:

```

case(opcode)
`OPC_STORE:

```

is the equivalent of:

```

case(opcode)
7'b0100011:

```

3.6 Running the Simulation

Open the file `sim-rtl.yml`, set the testbench's name to be `ALUTestbench`.

```
tb_name: &TB_NAME "ALUTestbench"
```

By typing `make sim-rtl` you will run the ALU simulation. You may change the testbench's name to `ALUTestVectorTestbench` to use the test vector testbench.

Once you have a working design, you should see the following output when you run either of the given testbenches:

```
# ALL TESTS PASSED!
```

To clean the simulation directory from previous simulations' files, type `make clean`.

3.7 Viewing Waveforms

As in the previous labs, you should use DVE to view waveforms.

1. List of the modules involved in the test bench. You can select one of these to have its signals show up in the object window.
2. Object window - this lists all the wires and regs in your module. You can add signals to the waveform view by selecting them, right-clicking, and doing `Add ζ To Wave ζ Selected Signals`.

3. Waveform viewer - The signals that you add from the object window show up here. You can navigate the waves by searching for specific values, or going forward or backward one transition at a time.

As an example of how to use the waveform viewer, suppose you get the following output when you run `ALUTestbench`:

```
# FAIL: Incorrect result for opcode 0110011, funct: 101:, add_rshift_type: 1
#      A: 0x92153524, B: 0xffffde81, DUTout: 0x490a9a92, REFout: 0xc90a9a92
```

The `$display()` statement actually already tells you everything you need to know to fix your bug, but you'll find that this is not always the case. For example, if you have an FSM and you need to look at multiple time steps, the waveform viewer presents the data in a much neater format. If your design had more than one clock domain, it would also be nearly impossible to tell what was going on with only `$display()` statements.

Add all the signals from `ALUTestbench` to the waveform viewer and you see the following window: The two highlighted boxes contain the tools for navigation and zoom. You can hover over the icons to find out more about what each of them do. You can find the location (time) in the waveform viewer where the test bench failed by searching for the value of `DUTout` output by the `$display()` statement above (in this case, `0x490a9a92`):

1. Selecting `DUTout`

2. Clicking `Edit > Wave Signal Search > Search for Signal Value > 0x490a9a92`

Now you can examine all the other signal values at this time. Compare the `DUTout` and `REFout` values at this time, and you should see that they are similar but not quite the same. From the `opcode`, `funct`, and `add_rshift_type`, you know that this is supposed to be an SRA instruction, but it looks like your ALU performed a SRL instead. However, you wrote

```
Out = A >>> B[4:0];
```

That looks like it should work, but it doesn't! It turns out you need to tell Verilog to treat `B` as a signed number for SRA to work as you wish. You change the line to say:

```
Out = $signed(A) >>> B[4:0];
```

After making this change, you run the tests again and cross your fingers. Hopefully, you will see the line:

```
# ALL TESTS PASSED!
```

If not, you will need to debug your module until all test from the test vector file and the hard-coded test cases pass.

3.8 Checkpoint #1: Simple test program

Checkoff due: Thursday, November 5, 2020

Congratulations! You've started the design of your datapath by drawing a pipeline diagram, and written and thoroughly tested a key component in your processor. You should now be well-versed in testing Verilog modules. Please answer the following questions to be checked off by a TA:

1. Show your pipeline diagram, and explain when writes and reads occur in the register file and memory relative to the pipeline stages.
2. Show your working ALU test bench files to your TA and explain your hard-coded cases. You should also be able to show that the tests for the test vectors generated by the Python script and your hard-coded test vectors both work.
3. In ALUTestbench, the inputs to the ALU were generated randomly. When would it be preferable to perform an exhaustive test rather than a random test?
4. What bugs, if any, did your test bench help you catch?
5. For one of your bugs, come up with a short assembly program that would have failed had you not caught the bug. In the event that you had no bugs and wrote perfect code the first time, come up with an assembly program to stress the SRA bug mentioned in the above section.

4 Checkpoint #2: Fully functioning core

Available on Tuesday, October 27, 2020

5 Checkpoint #3: Cache

Available on Tuesday, November 10, 2020

6 Checkpoint #4: Synthesis, PAR, & Power

Available Tuesday, November 17, 2020.

7 Grading

7.1 EECS 151:

70% *Functionality* at project due date: Your design will be subjected to a comprehensive test suite and your score will reflect how many of the tests your implementation passes.

25% *Final Report* and *Final Interview*: If your design is not 100% functional, this is your opportunity explain your bugs and recoup points.

5% *Checkpoints*: Each check-off is worth 1.25%. If you accomplished all of your checkpoints on time, you will receive full credit in this category.

Bonus 5% *Performance* at project due date: You must have a fully working design to score points in this section. You will receive up to 5 bonus points as your performance improves relative to your peers. Performance will be calculated using the Iron Law: $IPC * F$

7.2 EECS 251A:

60% *Functionality* at project due date: Your design will be subjected to a comprehensive test suite and your score will reflect how many of the tests your implementation passes.

10% *Set-Associative Cache*: Implementation and performance of the configurable set-associative cache.

25% *Final Report* and *Final Interview*: If your design is not 100% functional, this is your opportunity explain your bugs and recoup points.

5% *Checkpoints*: Each check-off is worth 1.25%. If you accomplished all of your checkpoints on time, you will receive full credit in this category.

Bonus 5% *Performance* at project due date: You must have a fully working design to score points in this section. You will receive up to 5 bonus points as your performance improves relative to your peers. Performance will be calculated using the Iron Law: $IPC * F$