CS 367 Project 3 – Fall 2024:

Task Manager

Due: Friday, November 15th, 11:59pm

This is to be an individual effort. No partners. No Internet code/collaboration.
Protect your code from anyone accessing it. Do not post code on public repositories.
No late work allowed after 48 hours; each day late automatically uses one of your tokens.

Core Topics: Processes, Signals, Unix I/O, C Programming Design (Helper Functions)

1 Introduction

For this assignment, you are going to use C to implement a Task Manager system called the **ZAKU** Task Manager. Once running, **ZAKU** maintains a list of several tasks, which can be executed, inspected, or otherwise managed (e.g. by killing or suspending a running task).

This assignment will help you to get familiar with the principles of process management in a Unix-like operating system. Our lectures on processes, signals, and Unix-I/O as well as Textbook Ch.8 (in particular 8.4 and 8.5) and 10.3 will provide good references to this project.

2 Project Overview

A typical **shell** (eg. the **bash** shell you enter commands into in Linux) receives instructions from the user in a terminal. In this project, the shell is the interface to our **Task Manager**. The shell would support a set of **built-in instructions**, which will then be interpreted by the shell, and acted on accordingly. In some cases, the instructions would be requests for the system to execute other **programs**. In that case, the shell would fork to create a new child process and execute the program in the context of the child.

The Task Manager also has the responsibility to **maintain a list of tasks** of interest, and to keep them organized. The user is able to enter programs, then execute them in the ***foreground*** (wait until the task completes) or ***background*** (allow the process to run while moving on to other things). The user can also control existing tasks by temporarily **suspending** them, **killing** them, or **deleting** them from the list altogether.

Finally, the user will have some additional capabilities, like **redirecting** the input or output of a process to or from a file, or to **pipe** the output of one task to another, or to **chain** the execution of one task with another. The Task Manager will allow the user to check the exit code of completed tasks. The shell provides some built-in instructions to help manage and list tasks, as well to execute and control running commands.

2.1 Features for ZAKU

Your implementation should be able to perform the following:

- Accept a single line of instruction from the user and perform the instruction.
    - The instruction may involve creating, deleting, or listing tasks.
    - The instruction may involve reading from or writing to a file.
    - The instruction may involve loading and running a user-specified program.
- The system must support any arbitrary number of simultaneous running processes.
    - **ZAKU** can either wait for a process to finish or let them run in the background.
- Perform basic management of tasks, whether they are in ready mode, running, or complete.
- Use file redirects and pipes to read input from or send output to a file or another process.
- Record the exit code of a completed task and use it to determine whether to start another task.
- Use signals to suspend/resume or terminate running processes, and track child activity.

We will describe each aspect of the system in more details with some examples below.

Specifications Document: **(Chapter 4 at the end has some guidance on starting your design)**
This document has of a breakdown of each of the features, looking at specific details, required logging, and sample outputs. This is an **open-ended** project that will require you to make your own design choices on how to approach a solution.

Read the whole document before starting!

2.2 Responsible Coding (i.e. trying not to crash Zeus)

Our processes management will require us to fork processes and receive signals. Every process we create uses system resources – sometimes we do not realize how many processes we have left lying around. To compound the situation, whenever we redefine our signal handlers, it may sometimes impact our process's natural ability to shut down cleanly. Hopefully we won't write any unintended fork bombs, but even then, we want to do our best to keep from creating too many unwanted processes. Here are some suggestions which will help.

2.2.1 Killing the Currently Running Process

Often, we may be in the middle of running our program, and either got stuck in a loop or simply want to exit out quickly. If this is the case, **do not use** `ctrl-z`. If you do this, it will not kill the process, it will simply put it to sleep, while still retaining all its resources in memory. Instead, use `ctrl-c`. If `ctrl-c` not work (often because we have redefined the signal handler), try `ctrl-\` instead. The former uses `SIGINT` whereas the latter uses `SIGTERM`. Either will, by default, terminate the program.

2.2.2 Checking for Running Process

When we are back at the `bash` prompt, we may be interested in knowing which processes we are currently running. That way, we can know if we have left behind any residual processes. The easiest way to do that is with the `ps ux` command. This will list out all processes under our name (including `bash` itself).

2.2.3 Killing Residual Processes

If we discover that we have left behind processes, we can use the `pkill` command at the `bash` prompt to kill processes by name. For example, we would use `pkill zaku` in order to kill of all our **zaku** processes. If **pkill** fails to kill one of our processes (often due to a corrupted signal handler), we can instead use **pkill -KILL zaku** in order to send a firmer and impossible to override kill message.

Always double check and clean up on Zeus!

3 Implementation Responsibilities

Your project handout consists of several files:

- The starting template code in **src/zaku.c**.
- Helper and logging functions are in the **src/** directory: **logging.c**, **parse.c**, and **util.c**.
- Headers are in the **inc/** directory: **logging.h**, **parse.h**, **util.h**, and **zaku.h**.
- A **Makefile** to build all components of the project.
- Several utility programs which you can use to help you test your text processing system.

You may take the existing starting template code in **src/zaku.c** and modify it. **This is the only file which you should modify**, and is the only file which you will be turning in. You should not need to include any additional header files, and you will not be allowed to use headers which change the project's linking requirements.

Your code will be tested on the Zeus system, so you are expected to do your development on Zeus. Even if you have a Linux or Mac system at home, there are subtle differences in the implementation of signal handling and process reaping from system to system.

You are responsible for making sure that your code functions correctly on Zeus.

When testing your code, there are some cases where you will be running external commands from within your system shell. You are allowed to use any normal commands on the system (e.g. **ls**), any of the provided utility programs, or any programs you have written yourself. It is **not** recommended that you try to execute any commands which have an interactive interface (e.g. **vim**) from within your shell. A group of commands (e.g. **wc**, **cat** or **grep**) would read from **stdin** if used without providing a file option. Those variations (w/o an input file) should only be used as the 2nd task of **pipe**. See 3.4.4.1 for **pipe** details.

3.1 Use of the Logging Functions

In order to keep the output format consistent, all of your output will be generated by calling the provided logging functions at the appropriate times to generate the right output from your program. Do not use your own print statements unless it is for your own debugging purposes. All logging output is encoded, which enables us to keep track of the activities of our shell.

The generated output from the log calls is what we use for grading!

The files **logging.c** and **logging.h** provide the functions for you to call from your code. Most of the log functions require you to provide additional information such as the Task Number (**task_num**), or possibly other info (e.g. Process ID, file name) to make the call. We will explain more details how and when each log function is used in the specifications below.

Check logging.h to see all logging facilities provided.

3.2 Prompt, Accepting, and Parsing User Instructions

Once started, the shell prints a welcome message and a prompt, and waits for the user to input an instruction. Each line from the user is considered as one instruction.

Logging Requirements:

- The user prompt must be printed by calling `log_prompt()`.
    - The call to `log_prompt()` is already present in the starting template code.

If a command line input is empty, it will be ignored by the shell. Otherwise, you will need to parse the user input into useful pieces. We provide a `parse()` function in `parse.h`. (the implementation is in `parse.c`). The provided template `src/zaku.c` has already included the code which calls `parse()` inside of `main()`. Feel free to use the provided `parse()` as is, or to implement your own parsing facility.

Appendix A has a detailed description of the input, output, and examples of using `parse()`.

In testing, make sure you use user commands following these rules:

- Every item in the line must be separated by one or more spaces;
- Many built-in instructions expect an additional Task Number argument.
- The `pipe` and `chain` built-in commands expects two Task Number arguments.
- Some built-in instructions (`start_fg` and `start_bg`) allow file redirection.
- Any instruction which is not built-in represents a command to be executed.
    - The program can be any real program, e.g. `ls`.
    - The program name is optionally followed by its command line arguments.

For this assignment, you can make the following assumptions:

- All user inputs are valid command lines (no need for format checking in your program).
- You may assume a bounded input line size and number of command arguments.
    - The maximum number of characters per input line is `100`.
    - The maximum number of arguments per program is `25`.
    - Check `zaku.h` for relevant constants defined for you (MAXLINE and MAXARGS).
- A command will not specify the path.
    - For example, you may see "`ls`" but not "`/usr/bin/ls`" in the input.

After calling `parse()`, the provided `src/zaku.c` leaves the design and implementation up to you as an **open-ended** project for you to solve. You are encouraged to write **many** functions and helper functions as well and you may add additional code in to `main()` as needed.

3.2.1 Basic Shell Instructions

A typical shell program supports a set of **built-in instructions** (internal functions that you design and implement in the shell itself). If a built-in instruction is received, the shell process must execute that directly. These following built-in instructions supported by our **ZAKU** system can be executed directly without the need to interact with any other parts of the system or forking any additional processes:

3.2.1.1 The "help" Built-In Instruction

`help`: when called, your shell should call the appropriate logging function to print a short description of the system, including a list of built-in instructions and their usage.

Logging Requirements:

- You must call `log_help()` to print out the predefined information.

Example Run (help instruction):

```
ZAKU$ help
[ZAKU-LOG] Instructions:
[ZAKU-LOG]     <COMMAND> [<ARGS>...],
[ZAKU-LOG]     help, quit, list, delete <TASK>,
[ZAKU-LOG]     start_fg <TASK> [<FILE>], start_bg <TASK> [<FILE>],
[ZAKU-LOG]     kill <TASK>, suspend <TASK>,
[ZAKU-LOG]     resume_fg <TASK>, resume_bg <TASK>,
[ZAKU-LOG]     fg <TASK>,
[ZAKU-LOG]     pipe <TASK1> <TASK2>
[ZAKU-LOG]     chain <TASK1> <TASK2>
[ZAKU-LOG]
[ZAKU-LOG] Brackets denote optional arguments
ZAKU$
```

3.2.1.2 The "quit" Built-In Instruction

`quit`: when called, your shell will exit normally on its own (this is built-in to main already).

Logging Requirements:

- You must add a call `log_quit()` to print out the predefined information.
- The shell will exit normally on its own, you just need to add this log message.

Assumptions:

- You can assume there are no non-terminated background processes when calling `quit`.
  - In other words: you may quit immediately; you are not responsible for clean-up.

Example Run (quit instruction):

```
ZAKU$ quit
[ZAKU-LOG] Thanks for using the ZAKU Task Manager! Good-bye!
[username@zeus-2 handout]$
```

3.3 Basic Task Management Instructions

This program is a task management system, so it has the ability to maintain several **tasks** (processes in execution) in various states at any time. Each task is assigned a **Task Number**, which is a positive integer value. In addition, every task must also track the **PID** of the process that is currently running and the **exit code** if that process has terminated. Each task must also store a copy of the **command** for the process that is running, so we can print out to the user.

```
ZAKU$ list
[ZAKU-LOG] 5 Task(s)
[ZAKU-LOG] Task 1: slow_cooker 10 (PID 997892; Suspended)
[ZAKU-LOG] Task 2: cal (PID 997871; Finished; exit code 0)
[ZAKU-LOG] Task 3: ls -a -l (Ready)
[ZAKU-LOG] Task 4: slow_cooker 50 (PID 998896; Killed; exit code 0)
[ZAKU-LOG] Task 5: slow_cooker 42 (PID 998900; Running)
ZAKU$
```

Any task is in one of five states: **Ready**, **Running**, **Suspended**, **Finished**, or **Killed**.

All tasks will start in the **Ready** state. However, running the program will cause it to change states as appropriate to indicate the current state of that task.

Each task has both a **Task Number** and a **Process ID (PID)**, so take care to keep from confusing them. The **Task Number** is the number we assign to our task in order to allow us to keep track of it in a list of our tasks in **ZAKU**. This is an internal number we use to quickly identify which task we wish to perform an operation on.

The **Process ID (PID)**, on the other hand, is a number assigned by the operating system to uniquely define and identify each process that is running. All processes on the operating system are guaranteed to have a unique PID. We must know the PID for each task to manage the process.

3.3.1 Task Number Assignment

Whenever a new task is created or deleted, we must follow certain rules about **Task Numbers**:

- Any new task is assigned a Task Number which is one greater than the largest Task Number.
    - For example, if current Task Numbers are 1, 3, and 5, the next Task Number will be 6.
- If there are no tasks, then the next new tasks will be assigned Task Number 1.
- If a Task is deleted, the remaining Task Numbers are **not** renumbered.

3.3.2 States and Logging

There are five states that each task can be in: **Ready**, **Running**, **Suspended**, **Finished**, or **Killed**. When you use certain Logging functions, you will need to pass in the current state for a task.

To make this easier, we have provided you with five `#define` constants (check `logging.h`). These defined constants are all integer values (ranging from 0 - 4), which you can use to pass in the correct state to these logging functions:

Ready State:	`LOG_STATE_READY`
Running State:	`LOG_STATE_RUNNING`
Suspended State:	`LOG_STATE_SUSPENDED`
Finished State:	`LOG_STATE_FINISHED`
Killed State:	`LOG_STATE_KILLED`

You are free to track the state of your task in any way you like, but when you need to pass the state into a logging function, you will need to use one of these five pre-defined constants.

3.3.3 Running a User Command to create a new Task

Any command which is not a built-in instruction (built-in examples: **quit**, **help**, etc.) should be interpreted as a user command. When a user command is entered into **ZAKU**, this will create and initialize a new task entry which describes the command.

Entering the command **will not execute the command**, but merely creates a task entry.

Once the task is created with the information from the command that was entered (eg. Instruction's `instruct` member, arguments (`argv`), and original command line entry (`cmd`)), then it will be in the **Ready** State, ready to be executed. Executing the task to run the process is handled by built-in instructions like `start_fg` or `start_bg`. Entering the command simply creates a Task.

Implement your own data structure for the Task and to maintain a list of any number of tasks.

Logging Requirements (when a Command is entered and a new Task is created):

- Call `log_task_init(task_num, cmd)` to indicate which Task Number was assigned.
    - The `cmd` is for the **complete** command line string which was provided as input.
        - As an example, if the user enters **ls -a -l** as the command, `cmd` will be "ls -a -l"
    - PIDs and Exit Codes are only relevant once we run the task; initialize these to 0.

Assumptions:

- The Task Number of the new task should be assigned consistent with the rules from 3.3.1.
- When a new command is entered, it is **not** immediately forked or executed.
    - Entering the command will only create a new task entry.
    - We would later use the `start_fg`, `start_bg`, `pipe`, or `chain` built-ins to run the task.
- The newly created tasks will be in the **Ready** state.
- We do NOT check for repeated user commands – each non built-in command typed in will always be taken as a new task.

Implementation Hints:

- You are required to have the ability to **maintain an arbitrary number of tasks**.
    - As arbitrary tasks may be deleted, consider using a data structure which lets you add an unlimited number of tasks, and to add or remove arbitrary elements easily.
- The command and its arguments are parsed for you by the code we have already written.
    - Check **Appendix A** for a detailed description of the input, output, and examples of the provided `parse()` functions.
        - The `parse()` function gives you a filled-in Instruction struct and the `argv` array.
    - You are not required to use our `parse()` function and you may modify main to call your own code to parse the user input, if you wish, but the given starter code does all of this string-processing work for you.
    - **Note:** The end of the main loop in main will free the instruction, `argv`, and `cmd`!
        - If you want your tasks to keep these, copy them into your data structures.
- Check out `util.c`, you may use any of the functions you find in there, if you find them useful.

Example Run (Command Entries and Output of log_task_init()):

```
ZAKU$ ls -al
[ZAKU-LOG] Adding Task ID 1: ls -al (Ready)
ZAKU$ cat fox.txt
[ZAKU-LOG] Adding Task ID 2: cat fox.txt (Ready)
ZAKU$ cal -3
[ZAKU-LOG] Adding Task ID 3: cal -3 (Ready)
ZAKU$ slow_cooker
[ZAKU-LOG] Adding Task ID 4: slow_cooker (Ready)
ZAKU$
```

3.3.4 Built-In Instructions Managing the List of Tasks

These following built-in instructions perform tasks related to the management of the list of tasks.

3.3.4.1 The "list" Built-In Instruction

This built-in command lists the total number of existing tasks as well as their details.

Logging Requirements:

- First call `log_num_tasks(num)` to indicate the number of tasks.
- Call `log_task_info(task_num, status, exit_code, pid, cmd)` once per task.
  - Tasks should be listed in order of **increasing** Task Number.
  - The `status` should be one of the `LOG_STATE_*` constants. (See 3.3.2)
  - The `exit_code` should be 0 unless the process has already completed execution.
  - The Process ID (`pid`) should be 0 while in the task is in the **Ready** state.
  - The `cmd` is the complete command line of the task. (See 3.3.3 for command info)

Assumptions:

- Tasks will begin in the **Ready State** (see 3.3.2 for states)
- `PID` and `Exit Code` are 0 for now (see 3.4 for how this might change during process execution).
- The number of tasks begins as 0 but changes as new tasks are created or deleted.

Example Run (Command entries and the list built-in instruction):

```
ZAKU$ ls -al
[ZAKU-LOG] Adding Task ID 1: ls -al (Ready)
ZAKU$ cal -3
[ZAKU-LOG] Adding Task ID 2: cal -3 (Ready)
ZAKU$ slow_cooker
[ZAKU-LOG] Adding Task ID 3: slow_cooker (Ready)
ZAKU$ list
[ZAKU-LOG] 3 Task(s)
[ZAKU-LOG] Task 1: ls -al (Ready)
[ZAKU-LOG] Task 2: cal -3 (Ready)
[ZAKU-LOG] Task 3: slow_cooker (Ready)
ZAKU$
```

3.3.4.2 *The "delete" Built-In Instruction*

`delete TASKNUM`: removes `TASKNUM` from the list of tasks.

Logging Requirements:

- On a successful delete, call `log_delete(task_num)`.
- If the selected task does not exist, call `log_task_num_error(task_num)` instead.
- If the task is currently busy, call `log_status_error(task_num, status)` instead.
    - A busy task is a **Running** or **Suspended** task; do not delete the task in this case.
    - The status would be `LOG_STATE_RUNNING` or `LOG_STATE_SUSPENDED`.

Assumptions:

- Only a task which is idle (**Ready**, **Finished**, or **Killed**) can be deleted.
- Once deleted, the task no longer exists and information about the task need not to be kept.

Example Run (list and delete built-in instructions):

```
ZAKU$ list
[ZAKU-LOG] 4 Task(s)
[ZAKU-LOG] Task 1: ls -l (Ready)
[ZAKU-LOG] Task 2: cat fox.txt (Ready)
[ZAKU-LOG] Task 3: cal -3 (Ready)
[ZAKU-LOG] Task 4: slow_cooker (Ready)
ZAKU$ delete 2
[ZAKU-LOG] Deleting Task ID 2
ZAKU$ delete 3
[ZAKU-LOG] Deleting Task ID 3
ZAKU$ delete 5
[ZAKU-LOG] Error: Task 5 Not Found in Task List
ZAKU$ my_echo 10
[ZAKU-LOG] Adding Task ID 5: my_echo 10 (Ready)
ZAKU$ list
[ZAKU-LOG] 3 Task(s)
[ZAKU-LOG] Task 1: ls -l (Ready)
[ZAKU-LOG] Task 4: slow_cooker (Ready)
[ZAKU-LOG] Task 5: my_echo 10 (Ready)
ZAKU$
```

3.4 Process Execution Instructions: Starting a Process

Our system would not be a Task Manager without the capability to execute tasks. In order to enable this capability, we will give our shell the ability to run external commands as separate processes. We can run an external command by first forking a child process, and then – within the context of the child – using one of the `exec()` variants (eg. `execv()`) to actually run the program.

Our system will allow us to run multiple concurrent processes. In fact, every existing task in the list is allowed to have its own corresponding process running as a child. If a task is currently running, it will be in the **Running** state. Before running, it starts in the **Ready** state. The execution of a task can be paused and the task switches to **Suspended** state. After the process completes, it will be in the **Finished** or **Killed** state, depending on how it terminated.

Assumptions:

- Any task will not have more than one associated child process at a time.

3.4.1 Execution Paths

When we execute external commands using `execv` or `execl`, we will also need to know the full **path** of the command to satisfy its first argument. To generate this, we will need to check two different paths for each command. These are: "`./`" and "`/usr/bin/`". Both of these paths must be checked, in this order, for an entered command, which will not have any path to begin with.

For example, if the user enters the command "`ls -al`", we need to try both "`./`" and "`/usr/bin/`" as the path argument to `execv`, **in that order**. We would first try to execute "`./ls`", and failing in that, we then execute the path in "`/usr/bin/ls`". Check the error code on `execv` or `execl` to see if the path was not found before checking the next one. If neither path leads to a valid program, then we would handle it as a path error and issue the appropriate log function.

Since the path argument of `execv` needs to be modified from the command by concatenating in "`./`" or "`/usr/bin/`", we will simply keep the original command name as **argv[0]**. So, if the user inputs "`ls -al`", then the path may be either "`./ls`" or "`/usr/bin/ls`" depending on which one works, but our `argv[0]` will still need to be "`ls`", which is what the user typed in.

3.4.2 The "`start_fg`" Built-In Instruction

This built-in command is how we run a non-interactive program (eg. `ls`, `wc`, `cat`, `cal`, `slow_cooker`). This will involve creating a child process to run the program in. You will need to execute the program with arguments, that are stored in your Task structure. You may have to try multiple paths (see 3.4.1) when executing the program.

start_fg `TASKNUM [< INFILE] [> OUTFILE]`: executes an external command

- The command is the external command associated with task ***`TASKNUM`.***
- Runs as a **foreground** process, meaning that the shell waits for the process to finish.
- If ***`INFILE`*** is specified, then the child process's input should be redirected from the file.
- If ***`OUTFILE`*** is specified, then the child process's output should be redirected to the file.
- The process status changes as it runs and eventually completes; see 3.3.2.
    - In this case, it will be set to **Running**.
- When the process completes, the task should record the process's exit code; see 3.5.3.

Logging Requirements:

- If the selected task does not exist, call `log_task_num_error(task_num)`.
- If the task is currently busy, call `log_status_error(task_num, status)` instead.
    - A busy task is a **Running** or **Suspended** task; do not execute the task in this case.
    - The status would be `LOG_STATE_RUNNING` or `LOG_STATE_SUSPENDED`.
- Call `log_status_change(task_num, pid, LOG_FG, cmd, LOG_START)`.
    - This should be called by the parent after forking a new process.
    - Use the task's full command line as `cmd`.
- If the command cannot be executed (`exec` failed), call `log_start_error(cmd)`.
    - Use the task's full command line as `cmd`.
    - Terminate the child with exit code 1.
- If a redirection is performed, call `log_redir(task_num, redir_type, filename)`.
    - `redir_type` is `LOG_REDIR_IN` or `LOG_REDIR_OUT` depending on which type.
- If a redirect file cannot be opened, call `log_file_error(task_num, filename)`.
    - Terminate the child with exit code 1.

- When the process terminates, there should be a log message; see 3.5.3.

Assumptions:

- The `start_fg` instruction can only be successfully run if the task is not currently busy.
- The `start_fg` will **not** be used on interactive programs (e.g. `vim`).
- All commands will be entered without a path (the path will be added by your code).
  - eg. The user enters `ls -a`, which has an instruction (argv[0]) that will be "`ls`"
    - You will first try to run the instruction with `execv` using a path of "`./ls`"
    - If that fails, you will then try using a path of "`/usr/bin/ls`"

Implementation Hints:

- We can use `fork()` to create a new child process.
  - You will need to give the child a new Process Group ID (PGID) after forking.
  - See **Appendix C** for information about how to do this.
- We can use either `execl() or execv()` to load a program and execute it in a process.
- Though `execl` or `execv` do not normally return, they **will** return with a `-1` value on error.
  - Example: if the path or command cannot be found.
  - Use the man pages for the command you wish to use to see the details.
  - Check both valid paths (`./` and `/usr/bin/`) with a command before calling it an error.
- Implement starting a task without file redirection **first** before adding the support to files.
- If a file is specified, open the file and redirect the child's standard in or out to the file.
  - Use `dup2()` to change the standard input or output the child **after** forking.
  - It is legal to request a redirect of both input **and** output at the same time.
  - Implement `start_fg` built-in without redirection before adding the redirect feature.
- Use `wait()` or `waitpid()` to wait for the child process to finish.
  - Either way, signals are relevant to process completion; see 3.5.6.
- **Yes, running a completed task would result in re-running the command.**

Example Run (start_fg instruction):

```
ZAKU$ ls -a
[ZAKU-LOG] Adding Task ID 1: ls -a (Ready)
ZAKU$ task_not_exit 1
[ZAKU-LOG] Adding Task ID 2: task_not_exit 1 (Ready)
ZAKU$ grep the
[ZAKU-LOG] Adding Task ID 3: grep the (Ready)
ZAKU$ start_fg 1
[ZAKU-LOG] Foreground Process 975680 (Task 1): ls -a (Started)
.   fish.txt  inc      my_echo   obj        slow_cooker    zaku
..  fox.txt   Makefile my_pause  src
[ZAKU-LOG] Foreground Process 975680 (Task 1): ls -a (Terminated Normally)
ZAKU$ start_fg 2
[ZAKU-LOG] Foreground Process 975682 (Task 2): task_not_exit 1 (Started)
[ZAKU-LOG] Error: task_not_exit 1: Command Cannot Load
[ZAKU-LOG] Foreground Process 975682 (Task 2): task_not_exit 1 (Terminated
Normally)
ZAKU$ list
[ZAKU-LOG] 3 Task(s)
[ZAKU-LOG] Task 1: ls -a (PID 975680; Finished; exit code 0)
[ZAKU-LOG] Task 2: task_not_exit 1 (PID 975682; Finished; exit code 1)
[ZAKU-LOG] Task 3: grep the (Ready)
ZAKU$
```

Example Run (start_fg instruction with file redirection):

```
ZAKU$ list
[ZAKU-LOG] 3 Task(s)
[ZAKU-LOG] Task 1: ls -a (PID 975680; Finished; exit code 0)
[ZAKU-LOG] Task 2: task_not_exit 1 (PID 975682; Finished; exit code 1)
[ZAKU-LOG] Task 3: grep the (Ready)
ZAKU$ start_fg 3 < fox.txt
[ZAKU-LOG] Foreground Process 981268 (Task 3): grep the (Started)
[ZAKU-LOG] Redirecting input from fox.txt for Task 3
the quick
the lazy
[ZAKU-LOG] Foreground Process 981268 (Task 3): grep the (Terminated Normally)
ZAKU$ start_fg 1 > out.txt
[ZAKU-LOG] Foreground Process 981714 (Task 1): ls -a (Started)
[ZAKU-LOG] Redirecting output to out.txt for Task 1
[ZAKU-LOG] Foreground Process 981714 (Task 1): ls -a (Terminated Normally)
ZAKU$
```

3.4.3 The "`start_bg`" Built-In Instruction

This built-in command is how we run a non-interactive program (eg. **`ls`**, **`wc`**, **`cat`**, **`cal`**, **`slow_cooker`**) in a way where we do not wait for the program to finish before prompting the user for more input. Like with **`start_fg`**, this will involve creating a child process to run the program in. You will need to execute the program with arguments, that are stored in your Task structure. You may have to try multiple paths (see 3.4.1) when executing the program.

***start_bg** `TASKNUM [< INFILE] [> OUTFILE]`: executes an external command.*

- Runs as a **background** process, meaning that the shell does not wait for the process to finish.
    - Signal handling will be necessary to detect process completion; see 3.5.6.
- The command is the external command associated with task ***`TASKNUM`*.**
- If ***`INFILE`*** is specified, then the child process's input should be redirected from the file.
- If ***`OUTFILE`*** is specified, then the child process's output should be redirected to the file.
- The process status changes as it runs and eventually completes; see 3.3.2.
- When the process completes, the task should record the process's exit code; see 3.5.3.

Logging Requirements:

- This logging requirements are nearly identical to those of the **`start_fg`** command.
- The exception: **`log_status_change(task_num, pid, LOG_BG, cmd, LOG_START)`**.
    - **`LOG_BG`** instead of **`LOG_FG`**.
- With background execution, process termination is logged only when the process completes.
    - This is not necessarily before returning to the shell prompt.

Implementation Hints:

- The **`start_bg`** built-in is like the **`start_fg`** built-in, but without waiting for process termination. It is a good idea to consider which part of code can be reused.
- **It's normal for a background process to print output after returning to the prompt.**
- **It's normal to not see the prompt.** You can hit enter at any time to get the prompt back.

Example Run (start_bg instruction):

```
ZAKU$ ls -a
[ZAKU-LOG] Adding Task ID 1: ls -a (Ready)
ZAKU$ slow_cooker 5
[ZAKU-LOG] Adding Task ID 2: slow_cooker 5 (Ready)
ZAKU$ start_bg 2
[ZAKU-LOG] Background Process 1823785 (Task 2): slow_cooker 5 (Started)
ZAKU$ [PID: 1823785] slow_cooker count down: 5 ...
[PID: 1823785] slow_cooker count down: 4 ...
[PID: 1823785] slow_cooker count down: 3 ...
start_fg 1
[ZAKU-LOG] Foreground Process 1823788 (Task 1): ls -a (Started)
.  ..  zaku  fox.txt  inc  Makefile  my_echo  my_pause    obj  slow_cooker  src
[ZAKU-LOG] Foreground Process 1823788 (Task 1): ls -a (Terminated Normally)
ZAKU$ [PID: 1823785] slow_cooker count down: 2 ...
[PID: 1823785] slow_cooker count down: 1 ...
[ZAKU-LOG] Background Process 1823785 (Task 2): slow_cooker 5 (Terminated Normally)
list
[ZAKU-LOG] 2 Task(s)
[ZAKU-LOG] Task 1: ls -a (PID 1823788; Finished; exit code 0)
[ZAKU-LOG] Task 2: slow_cooker 5 (PID 1823785; Finished; exit code 5)
ZAKU$
```

3.4.4 Pipes

When we want to send output from one process to another process, we can use a **pipe**. Similar to file redirection, output of one process can be redirected to a pipe, and input to another process can be redirected from a pipe. If one process sends to a pipe, and a second process reads from the same pipe, this lets the first process send data to the second process.

A pipe is like a double-ended file: we can write to one end of the pipe and read from the other end of the pipe. If we create a pipe before forking children, then both children will inherit the pipe and be able to use it to send data from one to the other.

Each pipe is **one-direction** only, meaning it has a **read-end** and a **write-end**. If you want two processes to talk to each other, you will need two pipes! For this program, we'll only need one, which will let process A send its output to process B.

Consider this scenario:

- Parent process **P** has two children, **A** and **B**.
  - **A** will be sending its output to **B**.
- **P** creates a pipe before forking **A** or **B**; thus, both **A** and **B** gain access to the pipe.
- **A** redirects its output to the *write-end* of the pipe and closes its *read-end*.
- **B** redirects its input from the *read-end* of the pipe and closes its *write-end*.
- **P** closes both its *read-end* and *write-end*, because it is not directly using either.
- Now, any output from **A** will get sent as input to **B**.

It is vitally important to close all unused pipe ends as described above.

Without doing so, **B** might never terminate, because it has no way of knowing when it has come to the end of its input (the unused pipe ends could *potentially* still be used to send input to **B**).

3.4.4.1 The "pipe" Built-In Instruction

In **ZAKU**, we can create two tasks and then use the **`pipe`** instruction to have the first task run and redirect all of its output to the second task, which will use that as its input.

For example, if the first task was **"`cat fox.txt`"** and second task was **"`wc -l`"**, then running the pipe command will run the first task, which outputs all the lines of text in fox.txt, sending them as the input into the second task, which will count the number of lines it received. The ultimate output on the screen will be the number 5, representing the 5 lines in fox.txt.

pipe `TASKNUM1 TASKNUM2`: executes two external commands connected by a pipe.

- Creates a pipe to allow output to be redirected from **`TASKNUM1`** and to **`TASKNUM2`**.
- Executes **`TASKNUM1`** as a background process (see **`start_bg`**).
  - Signal handling will be necessary to detect process completion; see 3.5.6.
- Executes **`TASKNUM2`** as the foreground process (see **`start_fg`**).
- The process status changes as it runs and eventually completes; see 3.3.2.
- When either process completes, the task should record the process's exit code; see 3.5.3.

Logging Requirements:

- If the two Task Numbers are identical, call **`log_pipe_error(task_num)`**.
  - Do not create a pipe or run either process.
- If either task cannot be executed due to invalid task number or incompatible state:
  - See logging requirements for **`start_fg`** and **`start_bg`** built-ins.
  - Do not create a pipe or run either process.
- If pipe creation fails, call **`log_file_error(task_num, LOG_FILE_PIPE)`**.
  - **`task_num`** is the Task Number of the first task, **`TASKNUM1`**.
  - Do not run either process.
- Call **`log_pipe(TASKNUM1, TASKNUM2)`** on success.
- See the logging requirements for the **`start_fg`** and **`start_bg`** commands for each process.
- With background execution, process termination is logged only when the process completes.
  - This is not necessarily before returning to the shell prompt.

Assumptions:

- Assume that neither process will use input or output file redirection.

Implementation Hints:

- The code used by the **`pipe`** built-in overlaps the **`start_fg`** and **`start_bg`** built-ins considerably.
- Do not forget to close the unused ends of the pipe as described in 3.4.4.

Example Run (pipe instruction):

```
ZAKU$ cat fox.txt
[ZAKU-LOG] Adding Task ID 1: cat fox.txt (Ready)
ZAKU$ grep the
[ZAKU-LOG] Adding Task ID 2: grep the (Ready)
ZAKU$ pipe 1 2
[ZAKU-LOG] Opening a pipe from Task 1 to Task 2
[ZAKU-LOG] Background Process 1946170 (Task 1): cat fox.txt (Started)
[ZAKU-LOG] Foreground Process 1946171 (Task 2): grep the (Started)
the quick
the lazy
```

```
[ZAKU-LOG] Background Process 1946170 (Task 1): cat fox.txt (Terminated Normally)
[ZAKU-LOG] Foreground Process 1946171 (Task 2): grep the (Terminated Normally)
ZAKU$
```

3.4.5 The "`chain`" Built-In Instruction

In **ZAKU**, the **`chain`** built-in instruction connects the execution of two tasks in a way so that the exit code of the 1st task determines whether the 2nd will be started.

***chain** TASKNUM1 TASKNUM2: executes two external commands conditionally.*

- Executes **`TASKNUM1`** as a foreground process (see **`start_fg`**).
- After **`TASKNUM1`** completes, check its exit status. Only if **`TASKNUM1`** completes normally (i.e. exit code == 0), executes **`TASKNUM2`** as a background process (see **`start_bg`**).
- The process status changes as it runs and eventually completes; see 3.3.2.
- When either process completes, the task should record the process's exit code; see 3.5.3.

Logging Requirements:

- If either task cannot be executed due to invalid task number or incompatible state:
  - See logging requirements for the **`start_fg`** and **`start_bg`** built-ins.
  - Do not run either process.
- Call **`log_chain(TASKNUM1, 0, TASKNUM2, LOG_CHAIN_START)`** if initial checking succeed before starting **`TASKNUM1`**.
- After **`TASKNUM1`** completes, check its exit status:
  - Call **`log_chain(TASKNUM1, TASKNUM1_exit_code, TASKNUM2, LOG_CHAIN_PASS)`** if ***`TASKNUM1`*** has 0 as its exit code before starting **`TASKNUM2`** as a background process.
  - Call **`log_chain(TASKNUM1, TASKNUM1_exit_code, TASKNUM2, LOG_CHAIN_FAIL)`** otherwise; do NOT start **`TASKNUM2`**.
- See the logging requirements for the **`start_fg`** and **`start_bg`** commands for each process.
- With background execution, process termination is logged only when the process completes.
  - This is not necessarily before returning to the shell prompt.

Assumptions:

- Assume that neither process will use input or output file redirection.

Implementation Hints:

- The code used by the **`chain`** built-in overlaps the **`start_fg`** and **`start_bg`** built-ins considerably.
- The code should also have a similar structure as the code for the **`chain`** built-in as both deal with more than one child process.

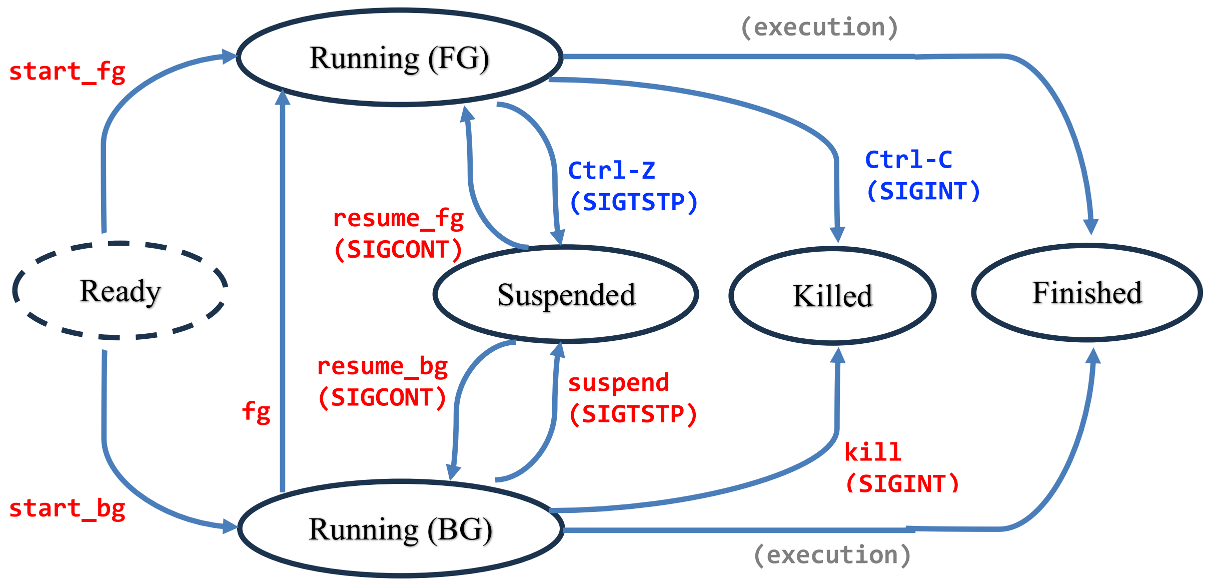
Example Run (chain instruction):

```
ZAKU$ list
[ZAKU-LOG] 2 Task(s)
[ZAKU-LOG] Task 1: my_echo 0 (Ready)
[ZAKU-LOG] Task 2: my_echo 5 (Ready)
ZAKU$ chain 1 2
[ZAKU-LOG] Executing a chain of Task 1 followed by Task 2
[ZAKU-LOG] Foreground Process 3403371 (Task 1): my_echo 0 (Started)
```

```
my answer is 0
[ZAKU-LOG] Foreground Process 3403371 (Task 1): my_echo 0 (Terminated Normally)
[ZAKU-LOG] Task 1 terminated with exit code 0 (success).
Task 2 will start next.
[ZAKU-LOG] Background Process 3403372 (Task 2): my_echo 5 (Started)
ZAKU$ my answer is 5
[ZAKU-LOG] Background Process 3403372 (Task 2): my_echo 5 (Terminated Normally)
ZAKU$ chain 2 1
[ZAKU-LOG] Executing a chain of Task 2 followed by Task 1
[ZAKU-LOG] Foreground Process 3405616 (Task 2): my_echo 5 (Started)
my answer is 5
[ZAKU-LOG] Foreground Process 3405616 (Task 2): my_echo 5 (Terminated Normally)
[ZAKU-LOG] Task 2 terminated with exit code 5 (fail).
Task 1 will NOT start.
ZAKU$
```

3.5 Process Control and Signaling

In addition to simply being able to execute external processes, we are also interested in being able to control running processes. We may want to kill a process before it is complete. Or we may want to suspend a running process and resume it later. This especially applies if we attempt using `^C` or `^Z` on a foreground process, from the terminal. The diagram below shows the potential process state transitions and the various events that might trigger those transitions.



Different colors for different kinds of events that might trigger status change of a process
- Built-in commands (signal sent)
- Keyboard combinations (signal sent)
- (normal execution): no intervention

We will discuss the implementation details of each command and signal processing below.

Assumptions:

- You can assume the user would never attempt to change the process status for a piped task or a chained task.

3.5.1 Basic Switch: the "`fg`" Built-in Instruction

fg* `TASKNUM`*: move Task* `TASKNUM` *from background to foreground.

Logging Requirements:

- If the selected task does not exist, call **`log_task_num_error(task_num)`**.
- If the task is not currently **Running**, call **`log_status_error(task_num, status)`** instead.
- Call **`log_fg(task_num, process_id, cmd)`** before switching the background process to foreground and wait for it to terminate.
- When the foreground process exit, additional logs should be generated; see 3.5.3.

Assumptions:

- **Running** background processes can be moved to foreground; others will produce an error log.

Implementation Hints:

- Moving a background process to foreground essentially means the task manager needs to wait for the termination of that process before it can print a prompt and accept new commands.
- The code should overlap partially with the code for **`start_fg`**.

Example Run (fg instruction):

```
ZAKU$ slow_cooker 8
[ZAKU-LOG] Adding Task ID 1: slow_cooker 8 (Ready)
ZAKU$ start_bg 1
[ZAKU-LOG] Background Process 3462153 (Task 1): slow_cooker 8 (Started)
ZAKU$ [PID: 3462153] slow_cooker count down: 8 ...
[PID: 3462153] slow_cooker count down: 7 ...
fg 1[PID: 3462153] slow_cooker count down: 6 ...
[PID: 3462153] slow_cooker count down: 5 ...

[ZAKU-LOG] Background Process 3462153 (Task 1): slow_cooker 8 switched to
Foreground
[PID: 3462153] slow_cooker count down: 4 ...
[PID: 3462153] slow_cooker count down: 3 ...
[PID: 3462153] slow_cooker count down: 2 ...
[PID: 3462153] slow_cooker count down: 1 ...
[PID: 3462153] slow_cooker count down: 0 ...
[ZAKU-LOG] Foreground Process 3462153 (Task 1): slow_cooker 8 (Terminated
Normally)
ZAKU$
```

3.5.2 Built-in Instructions Changing Process Status

3.5.2.1 `kill` `TASKNUM`: terminates the process with Task `TASKNUM` using `SIGINT`.

Logging Requirements:

- If the selected task does not exist, call **`log_task_num_error(task_num)`**.

- If the task is not currently **Running**, call `log_status_error(task_num, status)` instead.
- When signaling the kill, call `log_sig_sent(LOG_CMD_KILL, task_num, pid)`.
- As a side effect, the child may exit, which leads to additional logs; see 3.5.3.

Assumptions:
- **Running** processes can be killed; others will produce the error log.

Implementation Hints:
- A signal can be sent to a child process by using the `kill()` function.
- The signal which we want to send is `SIGINT`.
- This instruction only needs to signal the need to kill to the process.
    - Termination and clean-up would be handled separately; see 3.5.3.

Example Run (kill instruction):
```
ZAKU$ sleep 1000
[ZAKU-LOG] Adding Task ID 1: sleep 1000 (Ready)
ZAKU$ start_bg 1
[ZAKU-LOG] Background Process 1983555 (Task 1): sleep 1000 (Started)
ZAKU$ list
[ZAKU-LOG] 1 Task(s)
[ZAKU-LOG] Task 1: sleep 1000 (PID 1983555; Running)
ZAKU$ kill 1
[ZAKU-LOG] Cancel message sent to Task 1 (PID 1983555)
ZAKU$ [ZAKU-LOG] Background Process 1983555 (Task 1): sleep 1000 (Terminated by
Signal)
ZAKU$ list
[ZAKU-LOG] 1 Task(s)
[ZAKU-LOG] Task 1: sleep 1000 (PID 1983555; Killed; exit code 0)
ZAKU$
```

3.5.2.2 `suspend` `TASKNUM`: suspends the process with Task `TASKNUM` using `SIGTSTP`.
This will **suspend** the process associate with the task number. A suspended process won't run again on the CPU until it's been **resumed**.

Logging Requirements:
- If the selected task does not exist, call `log_task_num_error(task_num)`.
- If the task is currently idle, call `log_status_error(task_num, status)` instead.
    - An idle task is a **Ready**, **Finished** or **Killed** task; do not suspend such a task.
- When signaling, call `log_sig_sent(LOG_CMD_SUSPEND, task_num, pid)`.
- As a side effect, the child may be suspended, which leads to additional logs; see 3.5.3.

Assumptions:
- **Running** or **Suspended** processes can be suspended; others will produce the error log.
- Suspend a process that is already suspended will not change its status but you will still send the signal and call `log_sig_sent.`

Implementation Hints:
- A signal can be sent to a child process by using the `kill()` function.

  - Yes, it is still called "kill" if we are doing something benign like suspending.
- The signal which we want to send is **`SIGTSTP`**.
- This instruction only needs to signal the need to suspend to the process.
  - The suspension event would be handled separately; see 3.5.3.

3.5.2.3 `resume_fg` `TASKNUM`: resumes a suspended process with `TASKNUM` using `SIGCONT`.

This will take a process and resume it to be a foreground process.

Logging Requirements:

- If the selected task does not exist, call **`log_task_num_error(task_num)`**.
- If the task is not currently **Suspended**, call **`log_status_error(task_num, status)`** instead.
- When signaling, call **`log_sig_sent(LOG_CMD_RESUME, task_num, pid)`**.
- As a side effect, the child may be resumed, which leads to additional logs; see 3.5.3.

Assumptions:

- Only **Suspended** processes can be resumed; others will produce the error log.
- A resumed process should become a foreground process when it is eventually resumed.

Implementation Hints:

- A signal can be sent to a child process by using the **`kill()`** function.
  - Yes, it is still called "kill" if we are using it to resume a process.
- The signal which we want to send is **`SIGCONT`**.
- This instruction only needs to signal the need to resume to the process.
  - The resume event itself would be handled separately; see 3.5.3.

Example Run (suspend and resume_fg instructions):

```
ZAKU$ slow_cooker 5
[ZAKU-LOG] Adding Task ID 1: slow_cooker 5 (Ready)
ZAKU$ start_bg 1
[ZAKU-LOG] Background Process 917461 (Task 1): slow_cooker 5 (Started)
ZAKU$ [PID: 917461] slow_cooker count down: 5 ...
[PID: 917461] slow_cooker count down: 4 ...
suspend 1
[ZAKU-LOG] Suspend message sent to Task 1 (PID 917461)
ZAKU$ [ZAKU-LOG] Background Process 917461 (Task 1): slow_cooker 5 (Stopped)
ZAKU$ list
[ZAKU-LOG] 1 Task(s)
[ZAKU-LOG] Task 1: slow_cooker 5 (PID 917461; Suspended)
ZAKU$ resume_fg 1
[ZAKU-LOG] Resume message sent to Task 1 (PID 917461)
[ZAKU-LOG] Foreground Process 917461 (Task 1): slow_cooker 5 (Continued)
[PID: 917461] slow_cooker count down: 3 ...
[PID: 917461] slow_cooker count down: 2 ...
[PID: 917461] slow_cooker count down: 1 ...
[ZAKU-LOG] Foreground Process 917461 (Task 1): slow_cooker 5 (Terminated Normally)
ZAKU$
```

3.5.2.4 *`resume_bg` `TASKNUM`: resumes a suspended process with `TASKNUM` using `SIGCONT`.*

The only difference between this built-in and **`resume_fg`** is the resumed process should become a background process and the shell therefore does NOT wait for its termination to move on.

Logging Requirements:

- See **`resume_fg`**. The resumed child process will generate additional log messages as a background process.

Assumptions:

- Only **Suspended** processes can be resumed; others will produce the error log.
- A resumed process should become a background process when it is eventually resumed.

Implementation Hints:

- See **`resume_fg`**
- The code for this built-in would overlap substantially with the code for **`resume_fg`**.

Example Run (suspend and resume_bg instructions):

```
ZAKU$ slow_cooker 5
[ZAKU-LOG] Adding Task ID 1: slow_cooker 5 (Ready)
ZAKU$ start_bg 1
[ZAKU-LOG] Background Process 719736 (Task 1): slow_cooker 5 (Started)
ZAKU$ [PID: 719736] slow_cooker count down: 5 ...
[PID: 719736] slow_cooker count down: 4 ...
[PID: 719736] slow_cooker count down: 3 ...
suspend 1
[ZAKU-LOG] Suspend message sent to Task ID 1 (PID 719736)
[ZAKU-LOG] Background Process 719736 (Task 1): slow_cooker 5 (Stopped)
ZAKU$ list
[ZAKU-LOG] 1 Task(s)
[ZAKU-LOG] Task 1: slow_cooker 5 (PID 719736; Suspended)
ZAKU$ resume_bg 1
[ZAKU-LOG] Resume message sent to Task ID 1 (PID 719736)
[ZAKU-LOG] Background Process 719736 (Task 1): slow_cooker 5 (Continued)
[PID: 719736] slow_cooker count down: 2 ...
[PID: 719736] slow_cooker count down: 1 ...
ZAKU$ list
[ZAKU-LOG] 1 Task(s)
[ZAKU-LOG] Task 1: slow_cooker 5 (PID 719736; Running)
ZAKU$ [PID: 719736] slow_cooker count down: 0 ...
[ZAKU-LOG] Background Process 719736 (Task 1): slow_cooker 5 (Terminated Normally)
ZAKU$
```

3.5.3 Reaping Child Processes

When we exit a child process or change the state of a process, we will need to **reap** the process to determine its status. When a process ends, our main shell process will need to reap it at some point - this generally involves a call to **`waitpid()`**. We still have decisions to make regarding when and where the waiting takes place. We may perform the waiting after running a foreground process (see 3.4.2). We may also perform waiting whenever we receive a signal from the child (see 3.5.6).

No matter how we do the reaping, there are several things we know about the process. One, we can use the same call to detect for normal process termination as we do for signaled termination (e.g. `^C`), suspended processes, and resumed process. More importantly, when we control process states (e.g. by suspending and resuming it; section 3.5), we only need to send the signal to the process; later, when we have a chance to use `waitpid()`, we can update the task/process state in our program. This means that our `waitpid()` calls come with additional logging requirements:

Logging Requirements:

- On state change: `log_status_change(task_num, pid, type, cmd, transition)`.
  - Make this call whenever a process's state is affected.
  - `pid` is the Process ID of the process (not the Task Number).
  - `type` is `LOG_FG` for foreground processes, or `LOG_BG` otherwise.
  - `cmd` is the full user command associated with the task.
  - `transition` indicates how the process status was affected.
    - Can be: exited; terminated by signal; stopped; continued.
    - Uses `LOG_TERM`, `LOG_TERM_SIG`, `LOG_SUSPEND`, or `LOG_RESUME`.

Assumptions:

- Process state does not need to be updated when first signaled; it can defer until `waitpid()`.
- A `waitpid()` can be used to detect all process state changes of interest, not just termination.
  - Requires certain options to be set; check the `man` page for details.
- A resumed process will automatically become a foreground process.

Implementation Hints:

- By default, `waitpid()` blocks until a process finishes; we can make it poll for results instead.
  - If we use the `NOHANG` option, then it exits immediately if no process has finished yet.
  - Additional options can (and should) be used to check for stopped/continued processes.
  - Existing macros will help up read the status; see the `man` page for details.
    - `WIFEXITED, WIFSTOPPED, WIFSIGNALED, WIFCONTINUED`, etc.
- A call to `waitpid()` can be interrupted if a signal arrives.
  - If this happens, it may be necessary to restart the wait; be sure to check error codes.
- Multiple processes could end at roughly the same time; if so, wait multiple times in a row.
  - It may make sense to use a loop; keep waiting until no more processes are returned.
- A call to `waitpid()` allows us to record a process's exit code.
  - This is the best way to be sure to record exit codes for a terminated process!

3.5.4 Keyboard Interaction

Several keyboard combinations can trigger signals to be sent to the group of active processes. We will use these keyboard signals to help us control our current foreground process – otherwise we would have no way to enter commands to be able to stop or suspend our active process.

By default, your shell is the target for the keyboard interactions, which is actually one of the reasons why we do not support interactive programs being run. So, when you enter ctrl-C, it will go to your shell! Our command shell will have to use signal handling to detect keyboard inputs, and to forward those signals to the appropriate child process.

One other note is that, by default, all child processes belong to the same **process group** as their parent process. A process group is just a logical collection of processes, but the important part is that ctrl-C or ctrl-Z be sent to your shell, but they also go to every other process in the same group, including all of your child processes! We can fix this by putting each child process you create in their own group, which will separate them from your shell's group. See **Appendix C** for information on how to do this.

For this project, we only need to support two keyboard combinations:

- **`ctrl-C`**: A **`SIGINT`** (value 2) is sent to the foreground process.
    - The receiver process would terminate unless it has re-defined the handler of **`SIGINT`**.
- **`ctrl-Z`**: A **`SIGTSTP`** (value 20) is sent to the foreground process to suspend its execution.
    - The receiver process would suspend unless it has re-defined the handler of **`SIGTSTP`**.
- If there is no foreground process when these combinations are input, they should be ignored (i.e. they should not affect the execution of the command shell or any of the tasks).

Logging Requirements:

- Call **`log_ctrl_c()`** to report the arrival of **`SIGINT`** triggered by **`^C`**.
- Call **`log_ctrl_z()`** to report the arrival of **`SIGTSTP`** triggered by **`^Z`**.
- If there is no active process, the log calls should still be made.

Assumptions:

- Assume that **`SIGINT`** signals received by the shell process have only been triggered by **`^C`**.
- Assume that **`SIGTSTP`** signals received by the shell process have only been triggered by **`^Z`**.

Implementation Hints:

- Remember, keyboard-triggered signals are first sent to your shell process.
    - If you want the foreground child process to receive this signal, you will need to handle that signal and forward that to the appropriate child process.
- By default, a keyboard-triggered signal also gets sent to *all* processes, including children.
    - We can avoid this by putting different processes in different groups using **`setpgid()`**.
    - See **Appendix C** for specific instructions.
- Use **`sigaction()`** to change the default response to a particular signal.
- Use **`kill()`** to send or forward a signal we have received to another process.

Example Run (Keyboard ctrl-c / ctrl-z):

```
ZAKU$ sleep 1000
[ZAKU-LOG] Adding Task ID 1: sleep 1000 (Ready)
ZAKU$ start_fg 1
[ZAKU-LOG] Foreground Process 826993 (Task 1): sleep 1000 (Started)
^C[ZAKU-LOG] Keyboard Combination control-c Received
[ZAKU-LOG] Foreground Process 826993 (Task 1): sleep 1000 (Terminated by Signal)
ZAKU$ list
[ZAKU-LOG] 1 Task(s)
[ZAKU-LOG] Task 1: sleep 1000 (PID 826993; Killed; exit code 0)
```

```
ZAKU$ start_fg 1
[ZAKU-LOG] Foreground Process 827072 (Task 1): sleep 1000 (Started)
^Z[ZAKU-LOG] Keyboard Combination control-z Received
[ZAKU-LOG] Foreground Process 827072 (Task 1): sleep 1000 (Stopped)
ZAKU$ list
[ZAKU-LOG] 1 Task(s)
[ZAKU-LOG] Task 1: sleep 1000 (PID 827072; Suspended)
ZAKU$
```

3.5.5 Signal Concurrency Considerations

We will start to experience the fun and challenge of concurrent programming in this assignment.

In particular, if your design includes a global task list, be alert that **race conditions** might occur. A race condition is what we call it if one process performs an action too soon, or another one takes too long, and the two interfere in unexpected ways. A typical race in this project might happen if our main shell process is in the middle of updating the task list when the signal handler is triggered due to a child process completing. Due to the list being in an unstable state, the signal handler fails while trying search the same list.

For example, the following sequence is possible if no synchronization is provided:

1. The parent requests to delete Task 2, just before the running process in Task 3 finishes.
2. The parent unlinks Task 2 from the list and is just about to relink the remaining list.
3. `SIGCHLD` handler is executed and attempts to find task 3 in the list.
4. The handler fails because the list is cut off and might even get caught seeking through deallocated memory.

We recommend an approach where we protect ourselves against concurrency issues by **blocking** the `SIGCHLD` signal (and other signals that might trigger the updates of the global list) whenever we are about to perform a sensitive operation and **unblocking** it when we are done. Any signals which were sent while the signal was blocked are delivered right after the signal is unblocked.

It is a good idea to block signals before the call to `fork()` and unblock them only after the processes information has been updated in the task list. In fact, it is a good idea to block signals right before any update to any global data (such as the task list) and unblock afterwards. Both blocking and unblocking of signals can be implemented with `sigprocmask()`. If we create functions for blocking and unblocking, it is easy to trigger them when needed.

Implementation Hints:

- Make functions to block and unblock signals on request.
    - Blocking can be implemented using the `sigprocmask()` function.
- Block signals right before any update to a global data structure (e.g. a task list).
    - Unblock when done with the update.
    - Includes right before forking.
- Children inherit the blocked set of their parents.
    - They are responsible for unblocking any signals blocked by their parents.
    - In particular, unblock all signals before calling `execl()` or `execv()`.

3.5.6 Signal Handling with SIGCHLD

If you have already implemented the keyboard interrupts described in section 3.5.4, then you already have signal handling built into your code. If you have taken the signal blocking precautions described in 3.5.5, then your code will be reasonably well-prepared to handle concurrent processing scenarios which may arise due to signaling and forked children. Let us talk about one more important signal which you will be responsible for handling.

When a child process changes state, it automatically sends out a `SIGCHLD` signal to the parent. This includes when the process terminates, or is killed, or suspends, or resumes. To find out when our processes change state, we should set up a signal handler to handle these child events. It is true that we can wait on a process to find out when it ends, but our program will not spend all its time waiting; it is more reliable to use signals to determine when it ends.

Assumptions:

- The only signals we are responsible for handling are `SIGINT`, `SIGTSTP`, and `SIGCHLD`.

Implementation Hints:

- A child inherits its parent's handlers, so it should first reset the handlers to the default.
    - See **Appendix D** for more details.
- Use blocking (see 3.5.5) outside the handler to protect your sensitive logic from signals.
- Signals which were raised multiple times while blocking are delivered once after unblocking.
    - If `SIGCHLD` is triggered, reap in a loop until you are sure there are no more processes.
    - A `waitpid()` with correct arguments exit immediately, so we can use it to poll.
- Commands such as `kill` or `suspend` do not need to directly quit or suspend the process.
    - If they signal the process, the action can take place in the signal handler. (see 3.5.2)
- The textbook uses `signal()`, **which has been deprecated** and replaced by `sigaction()`.
    - Do not use `signal()`. Use `sigaction()` instead.
- Avoid using `stdio.h` functions inside a signal handler.
    - The handler's call may interfere with an interrupted call from the main code.
    - Especially applies to the `errno` of a call; two different calls use the same `errno`.
    - If you need to print debug statements, use `write()` with `STDOUT_FILENO` directly.

4 Getting Started

First, get the starting code (`p3_handout.tar`) from the same place you got this document. Once you un-tar the handout on Zeus (using `tar xvf p3_handout.tar`), you will have the following files in the `p3_handout` directory:

In the src/ Subdirectory:

- `zaku.c` – **This is the only file you will be modifying (and submitting).** There are stubs in this file for the functions that will be called by the rest of the framework. Feel free to define more functions if you like but put all of your code in this file!
- `logging.c` – This has a list of provided logging functions that you need to call at the appropriate times.

- `parse.c` – This has a list of provided parsing functions that you could use to divide the user command line into useful pieces.
- `util.c` – This includes utility functions which you may call to automate the process of copying and clearing strings and argument lists.
- `my_pause.c` – a C program that can be used as local program to load/execute in shell. It will not terminate normally until `SIGINT` has been received three times. Feel free to edit the C source code to change its behavior. This program helps to test signal handling.
- `slow_cooker.c` – a C program that can be used as local program to load/execute in shell. It will slowly count down from 10 to 0 then terminate normally by exiting with the original count value. You can specify a different starting value or edit the C source code to change its behavior. This program will help you test multiple concurrent processes.
- `my_echo.c` – a C program that can be used as local program to load/execute in shell. It takes an integer argument and use it as the return value / exit status. The default return value / exit status is 0. You can change the value to test exit status with shell. This program will help you test whether your program correctly handles exit codes.

In the inc/ Subdirectory:

- `zaku.h` – This has some basic definitions and includes necessary header files.
- `logging.h` – This has the prototypes of logging functions implemented in `logging.c`.
- `parse.h` – This has the prototypes of parsing functions implemented in `parse.c`.
- `util.h` – This has the prototypes of parsing functions implemented in `util.c`.

In the main handout Directory:

- `Makefile` – to build the assignment (and clean up).
- `fox.txt` – a simple text file for convenient testing (of file redirection).

To get started on this project, read through the provided code in `zaku.c` and the constants and definitions in `zaku.h`, `parse.h`, `util.h`, and `logging.h`. Make sure you understand the input/output of the provided parsing facility, in particular the structure of `argv[]` and `Instruction`. You may use provided helper functions declared in the header files for your own purposes.

It is a very good idea to **start early**, and not try to do the whole project in one swoop. Implement feature by feature and test the features as you implement them. The more complex features build off of the simpler features, so it is a good idea to make sure that the earlier parts of the project work reliably before attempting something more involved.

If you are not sure where to begin, the order of topics in this design document serves as a reasonable suggestion for a potential order of implementation: begin with instructions which have no relation to the rest of the project; add task management capability; add process execution; add signal handling and refined process control. Spend some time designing the overall layout on paper before starting to code. Once you have this in your design, add the various features in an order which lets you ensure that your code works.

For testing, you may use any of the programs which are included in your handout; any programs you write yourself; or any utilities which are already available on the system. Some programs which may be helpful for debugging include, but are not limited to: `ls`, `grep`, `cal`, `cat`, `sort`, or `sleep`.

After this, make sure all of the details in each section of this document are met, such as all of the required logging is present (**this is critically important – all grading is done from these log calls)**, that you have all the cases handled, and that all features are incorporated. The more modular you make your design, the easier it will be to debug, test, and extend your code.

When it comes to debugging, `gdb` works just as well for a program which forks as it does with any other program. However, when a process forks, the debugger can only follow one of the two branches which are created. By default, `gdb` will only follow the **parent** process. However, we can choose to follow the **child** process instead. In order to change the follow mode, we would enter the command "`set follow-fork-mode child`" at the `gdb` prompt.

We always encourage the use of `valgrind` to check for memory leaks, because memory leaks are often the sign of a deeper problem, and it is a good programming habit to eliminate them. However, **we will not be testing for memory** leaks when we grade your submissions. This is because memory leaks may be tricky to track down in a program with multiple concurrent processes, and we believe that your efforts may be better spent elsewhere. Be forewarned that even if you have eliminated all memory leaks in your program, `valgrind` may still report leaks due to child processes which have terminated early.

5 Submitting & Grading

Submit this assignment electronically on Canvas. Note that the only file that gets submitted is `zaku.c`. **Make sure to put your G# and name as a commented line in the beginning of your program.**

You can make multiple submissions; but we will test and grade ONLY the latest version that you submit (with the corresponding late penalty, if applicable).

Important: Make sure to submit the correct version of your file on Canvas! Submitting the correct version late will incur a late penalty; and submitting the correct version 48 hours after the due date will not bring any credit.

Questions about the specification should be directed to the CS 367 Piazza forum.

Your grade will be determined as follows:

- **20 points** - code & comments. Be sure to document your design clearly in your code comments. This score will be based on reading your source code.
- **80 points** – correctness. We will be building your code using the `zaku.c` code you submit along with our code.
    - If you program does not compile, **we cannot grade it**.

- If your program compiles but does not run, **we cannot grade it.**
- We will give partial credit for incomplete programs that compile and run.
- We will use a series of programs to test your solution.

6 Tips & Tricks

Global variables are allowed.

Normally, we hate global variables. They are easy to confuse and abuse, promote inflexible code, and lead to unexpected errors because they are so easy to misuse. Signal handlers are one of the rare exceptions – signal handling is inherently global, and global variables are one of the few ways to share data with a signal handler. The signal handlers essentially force us to use global variables. Thus, for this project, reasonable use of global variables is allowed. It is a good idea to keep the use to a minimum – only where necessary to share data with a signal handler.

Careless use of strcat() leads to errors.

If we try to write C code which says `strcat("/usr/bin", argv[0])`, it will typically produce an error. Why? For one, we would prefer to use `strncat` in favor of `strcat`, because the latter is not memory-safe. More notably, C does not automatically resize string arrays for us. If we use the hard-coded string `"/usr/bin"`, it has **only allocated space for that string**! Anything we append beyond that point is overwriting unknown data.

Instead, we should make sure that we create enough space to store the complete string, and we should use `strncat` to make sure that we do not overrun the space.

Make a copy of any strings that you plan to use.

If we link to the original string instead of duplicating it, we may have a problem if the original changes. This is especially true if we create a pointer which points directly to the `cmd` variable in `main()`. The moment that `cmd` gets updated (which happens every time we prompt for input), the contents are reset. If we did not make a copy, we would have lost our data. It also applies to `argv` or anything from `inst`.

Have a look at `util.h` for functions which will help with duplicating strings and data structures.

Trying to terminate a process which is asleep has no effect.

It is normal behavior that sending a `SIGINT` to a sleeping process will not kill it. If we want to terminate the process, wake it up first before sending the signal.

Some of the quirks of concurrency are normal.

When running commands in the background, we may see some outputs which may intuitively seem unusual, but are in fact quite normal. For example, when running a background process, we may see log messages appear in a different order than expected due to the order that events are processed. This is not necessarily a problem.

Another common result is for the command prompt to “disappear” when running a background process, as the program apparently gets stuck in an infinite loop. Fortunately, appearances can often be deceiving. What often happens is that the command prompt appears early on, then gets buried by output as the background process continues to run. Look higher up on the terminal to see if the prompt is there. Try to press enter to get a new prompt. If this works, everything is ok.

Finally, we may sometimes see a double-prompt (a second prompt appearing due to no particular action on our part). This may happen automatically if the system is waiting at the command prompt, and suddenly gets interrupted by a signal. A re-prompt in this situation is considered normal behavior.

Appendix A: User Input Line

The provided `parse.c` includes a `parse()` function that divides the user command into useful pieces. To use it, provide the full command line as input in `cmd_line`, and previously allocated data structures `inst` and `argv`. The `parse()` function will then populate `inst` and `argv` based on the contents of `cmd_line`.

```
void parse(const char *cmd_line, Instruction *inst, char *argv[]);
```

- `cmd_line`: the line typed in by user **WITHOUT** the ending newline (`\n`).
- `inst`: the pointer to an `Instruction` record which is used to record the additional information extracted from `cmd_line`. The detailed definition of the struct is as below.

```
typedef struct instruction_struct{
        char *instruct;   // the instruction we're running

        int num;          // the Task Number associated with the instruction,
                          // or 0 if none/default

        int num2;          // the 2nd Task Number associated with the instruction,
                          // or 0 if none/default

        char *infile;     // the input filename associated with the instruction

        char *outfile;    // the output filename associated with the instruction
} Instruction;
```

- `argv`: an array of `NULL` terminated char pointers with the similar format requirement as the one used in `execv()`.
    - `argv[0]` should be the name of the program to be loaded and executed;
    - the remainder of `argv[]` should be the list of arguments used to run the program
    - `argv[]` must have `NULL` following its last argument member.

Assumptions: You can assume that all user inputs are valid command lines (no need for format checking in your program). You can also assume that the maximum number of characters per command line is `100` and the maximum number of arguments per executable is `25`. Check `zaku.h` for relevant constants defined for you.

Notes of Usage:

- The provided `parse.c` also has supporting functions related to command line parsing, including the initialization/free of `inst`. Check `parse.h` for details.
- Similar code to allocate or free `argv` can be found in `util.h`.
- The provided `zaku.c` already includes necessary steps to make the call to `parse()`.
- The provided `zaku.c` also has a `debug_print_parse()` function you could use to check the return of `parse()`. It's for debugging only.
- The debug messages printed by the program are fully optional and can be disabled by changing the `debug` define to 0 instead of 1.

Appendix B: Useful System Calls

Here we include a list of system calls that perform process control and signal handling. You might find them helpful for this assignment. The system calls are listed in alphabetic order with a short description for each. Make sure you check our textbook, lecture slides, and Linux manual pages on `zeus` to get more details if needed.

- `int dup2(int oldfd, int newfd);`
    - It makes `newfd` to be the copy of `oldfd`; useful for file redirection.
    - Textbook Section **10.9**
    - Manual entry: ***man dup2***

- `int execv(const char *path, char *const argv[]);`
- `int execl(const char *path, const char *arg, ...);`
    - Both are members of exec() family. They load in a new program specified by `path` and replace the current process.
    - Textbook Section **8.4**
    - Manual entry: ***man 3 exec***

- `void exit(int status);`
    - It causes normal process termination.
    - Textbook Section **8.4**
    - Manual entry: ***man 3 exit***

- `pid_t fork(void);`
    - It creates a new process by duplicating the calling process.
    - Textbook Section **8.4**
    - Manual entry: ***man fork***

- `int kill(pid_t pid, int sig);`
    - Used to send signal `sig` to a process or process group with the matching `pid`.
    - Textbook Section **8.5.2**
    - Manual entry: ***man 2 kill***

- `int open(const char *pathname, int flags);`
- `int open(const char *pathname, int flags, mode_t mode);`
    - Opens a file and returns the corresponding file descriptor.
    - Textbook Section **10.3**
    - Manual entry: ***man 2 open***

- `int pipe(int pipefd[2]);`
    - It creates a new pipe, initializing file descriptor at either end of the pipe.
    - Manual entry: ***man pipe***

- `int setpgid(pid_t pid, pid_t pgid);`
    - It sets the group id for the running process.

  - Textbook Section **8.5.2**
  - Manual entry: ***man setpgid***

- **`int sigaction(int signum, const struct sigaction *act, struct sigaction *oldact);`**
  - Used to change the action taken by a process on receipt of a specific signal.
  - Textbook Section **8.5.5 (pp.775)**
  - Manual entry: ***man sigaction***

- **`int sigaddset(sigset_t *set, int signum);`**
- **`int sigemptyset(sigset_t *set);`**
- **`int sigfillset(sigset_t *set);`**
  - The group of system calls that help to set the mask used in **`sigprocmask`**.
  - **`sigemptyset()`** initializes the signal set given by **`set`** to empty, with all signals excluded from the **`set`**.
  - **`sigfillset()`** initializes **`set`** to full, including all signals.
  - **`sigaddset()`** adds signal **`signum`** into **`set`**.
  - Textbook Section **8.5.4**
  - Manual entry: ***man sigsetops***

- **`int sigprocmask(int how, const sigset_t *set, sigset_t *oldset);`**
  - Used to fetch and/or change the signal mask; useful to block/unblock signals.
  - **`how`** is one of **`SIG_BLOCK`**, **`SIG_UNBLOCK`**, or **`SIG_SETMASK`**
  - Textbook Section **8.5.4, 8.5.6**
  - Manual entry: ***man sigprocmask***

- **`unsigned int sleep(unsigned int seconds);`**
  - It makes the calling process sleep until **`seconds`** seconds have elapsed or a signal arrives which is not ignored.
  - Note: **`sleep`** measures the elapsed time by absolute difference between the start time and the current clock time, regardless whether the process has been stopped or running. This means if you suspend and resume it, it will check to see if x seconds have passed since starting.
    - So, if you use sleep 5, then ctrl-Z 1 second into the run, wait 30 seconds, and then resume it, it will see at least 5 seconds have elapsed since it started and will immediately quit, even though it only 'ran' for 1 second.
  - Textbook Section **8.4.4**
  - Manual entry: ***man 3 sleep***

- **`pid_t waitpid(pid_t pid, int *status, int options);`**
  - Used to wait for state changes in a child of the calling process, and obtain information about the child whose state has changed.
  - Textbook Section **8.4.3**
  - Manual entry: ***man waitpid***

- **`ssize_t write(int fd, const void *buf, size_t count);`**

  - It writes up to **`count`** bytes from the buffer pointed **`buf`** to the file referred to by the file descriptor **`fd`**. The standard output can be referred to as **`STDOUT_FILENO`**.
  - Textbook Section **10.4**
  - Manual entry: ***man 2 write***

Appendix C: Process Groups

Every process belongs to exactly one process group.

```
#include <unistd.h>
```

When a parent process creates a child process, the child process inherits the same process group from the parent.

```
#include <unistd.h>

int setpgid(pid_t pid, pid_t pgid);
```

- The **`setpgid()`** function shall set process group ID of the calling process.
  - In particular, **`setpgid(0,0)`** will create a new process group with just itself.

In practical terms, the one place that your code must use these will be a call to **`setpgid(0,0)`**, from the child process, immediately after forking.

References:

- http://man7.org/linux/man-pages/man3/getpgrp.3p.html
- http://man7.org/linux/man-pages/man3/setpgid.3p.html
- Textbook Section 8.5.2 (pp.759)

Appendix D: System Call sigaction()

The **sigaction()** system call is used to change the action taken by a process on receipt of a specific signal. The **sigaction()** function has the same basic effect as **signal()** but provides more powerful control. It also has a more reliable behavior across UNIX versions and is recommended to be used to replace **signal()**.

```
#include <signal.h>
int sigaction (int signum, const struct sigaction *action,
          struct sigaction *old_action);
```

- **signum** specifies the signal.
    - It can be any valid signal except **SIGKILL** and **SIGSTOP**.
- For non-**NULL** **action**, a new action for signal **signum** is installed from **action**.
    - It could be the name of the signal handler.
- If **old_action** is non-**NULL**, the previous action is saved in **old_action**.

Example program:

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <signal.h>

void sigint_handler(int sig) {      /* signal handler for SIGINT */
  write(STDOUT_FILENO, "SIGINT\n", 7);
  exit(0);
}

int main(){
  struct sigaction new; /* sigaction structures */
  struct sigaction old;

  memset(&new, 0, sizeof(new));
  new.sa_handler = sigint_handler;  /* set the handler */
  sigaction(SIGINT, &new, &old);    /* register the handler for SIGINT */

  int i=0;
  while(i<100000){                  /* this will loop for a while */
      fprintf(stderr, "%d\n", i);/* break loop by Ctrl-c to trigger SIGINT */
      sleep(1);
      i++;
  }
  return 0;
}
```

References:

https://www.gnu.org/software/libc/manual/html_node/Sigaction-Function-Example.html
http://man7.org/linux/man-pages/man2/sigaction.2.html

Appendix E: ZAKU Index

Here we include a list of **ZAKU** features that you need to implement and a quick reference to the relevant sections of this document.

Group	Details	Section No.	Page No.
`Built-in Command`	**`help`**	3.2.1.1	5
	`quit`	3.2.1.2	5
	`list`	3.3.4.1	8
	`delete`	3.3.4.2	9
	`start_fg`	3.4.2	10-12
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	`pipe`	3.4.4	14-15
	`chain`	3.4.5	15-16
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	`kill`	3.5.2.1	17-18
	`suspend`	3.5.2.2	18-19
	`resume_fg`	3.5.2.3	19
	`resume_bg`	3.5.2.4	20
`Keyboard Combination`	**`Ctrl-C`**	3.5.4	21-23
	`Ctrl-Z`	3.5.4	21-23
`External Command`	**`Any command that is not a built-in`**	3.3	7-8