Pack Lab Overview

Rev 3.1

CS213 – Intro to Computer Systems

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High-level overview

- You will be given a utility that can “Pack” a file

- Supports three operations
  - Checksums - ensure data integrity
  - Encrypts - file is only readable with password
  - Compresses - reduces file size losslessly

- Your goal: write the “unpack” utility
  - Unpacks a file and writes data to a new output file

Getting the lab files

- A tar of the lab file is available in the ~cs213/HANDOUT directory
  - Must be on the class server: moore.wot.eecs.northwestern.edu

- Steps:
  1. SSH into moore
  2. Make a directory to hold the lab files in
  3. Run the following command

```
tar xvf ~cs213/HANDOUT/packlab-starter.tar
```

- That will get you all the necessary lab files

Code files

- `unpack.c`
  - Application for unpacking files
  - Already written!

- `unpack-utilities.c`
  - Utilities used by the application to perform operations
  - **You need to write this**

- `unpack-utilities.h`
  - Header file for unpacking utilities
  - Includes comments about the purpose of each function

- `test-utilities.c`
  - Test code for unpacking utilities
  - **You will add to this to test your code**

Getting started

1. Understand what the existing code is doing
2. Implement `parse_header()`
3. Implement `calculate_checksum()`
4. Implement `lfsr_step()`
5. Implement `decrypt_data()`
6. Implement `decompress_data()`

Test as you go! Each of these functions can be tested independently

Submitting the lab files

- Gradescope will be used for grading your code
  - You can submit any number of times
  - But you won’t get feedback until after the deadline, except whether it compiles
- To submit your code, run:

```
~cs213/HANDOUT/submit213 submit --hw packlab unpack-utilities.c
```

  - The first time you run the tool, it will ask you to log in with your Gradescope credentials
- You MUST also mark your partnership on Gradescope. Click the button labeled “Group Members” and select your partner from the dropdown
  - Unfortunately, you have to do this each time you submit code

Grading

- 19% for correct implementations of the five major functions in `unpack-utilities.c`
  - `parse_header()`, `calculate_checksum()`, `lfsr_step()`, `decrypt_data()`, `decompress_data()`
- 5% for the entire unpack program working on the `example_files/`
- With some partial credit given for partially working code
- Your code should successfully unpack any file that meets the specification, and should also error and exit when necessary
  - Invalid files, for example
- You are not graded on your tests

Changelog

- 1.0: Initial release
- 2.0: Correction, decryption uses LFSR state as little-endian
  - 2.1: Clarified that the initial state for the LFSR is based on password
  - 2.2: Added a link to a youtube video on LFSR
  - 2.3: Clarify `data_offset`, redraw LFSR xor gates, clarify `input_data`, note the need for bit masking
- 3.0: Add submission steps, clarify grading better
  - 3.1: Clarify grading, clarify checksum implementation, example of decompression

Outline

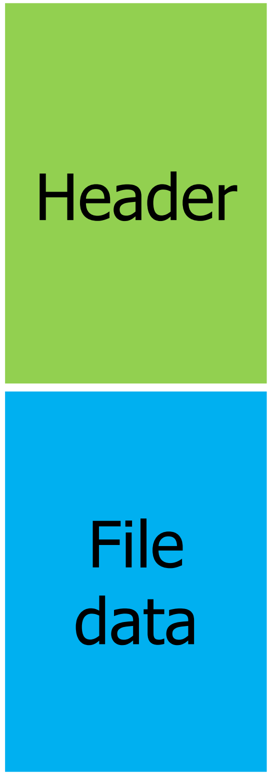
- **Header Format**
- Checksums
- Encryption
  - Linear-Feedback Shift Register
  - Stream Cipher
- Compression
  - Compression dictionary
  - Escape sequences
- Testing

Format of packed files

- "Packed" files have two sections of bytes
  - Header then File data

- Header (4–22 bytes)
  - Identification and configuration of the packed file
  - Includes "magic bytes" and version to identify a packed file
  - Includes flags to determine which options are applied
  - Includes configurations for particular options

- File Data (0–2^{64} bytes)
  - Contents of the original file
  - Possibly encrypted and compressed



Minimal header: Compression and Checksum disabled

Byte offset	0	1	2	3
0	Magic: 0x0213		Version: 0x01	Flags

- Magic
  - Identifies this file as a “packed” file. Always 0x0213 (big-endian)
- Version
  - Identifies which version of the “pack” protocol is used. Always 0x01
- Flags
  - Determines which options are applied to the file
  - 0 - disabled, 1 - enabled

Bit	7	6	5	4	3	2	1	0
Value	Compress?	Encrypt?	Checksum?	Unused: all zero				

Compression enabled, Checksum disabled

Byte offset	0	1	2	3
0	Magic: 0x0213		Version: 0x01	Flags
4	Dictionary[0]	Dictionary[1]	Dictionary[2]	Dictionary[3]
8	Dictionary[4]	Dictionary[5]	Dictionary[6]	Dictionary[7]
12	Dictionary[8]	Dictionary[9]	Dictionary[10]	Dictionary[11]
16	Dictionary[12]	Dictionary[13]	Dictionary[14]	Dictionary[15]

- Compression dictionary
  - 16-byte array used for compression
  - Contains 16 most-used bytes from the original uncompressed file

Compression disabled, Checksum enabled

Byte offset	0	1	2	3
0	Magic: 0x0213		Version: 0x01	Flags
4	Checksum			

- Checksum
  - 16-bit unsigned checksum value (big-endian)
  - Was computed on the data after compression and encryption

- Note: you don’t need to calculate a checksum here, that will happen later in a different function
  - And comparing the two checksums happens for you in `unpack.c`

Full header: Compression and Checksum enabled

Byte offset	0	1	2	3
0	Magic: 0x0213		Version: 0x01	Flags
4	Dictionary[0]	Dictionary[1]	Dictionary[2]	Dictionary[3]
8	Dictionary[4]	Dictionary[5]	Dictionary[6]	Dictionary[7]
12	Dictionary[8]	Dictionary[9]	Dictionary[10]	Dictionary[11]
16	Dictionary[12]	Dictionary[13]	Dictionary[14]	Dictionary[15]
20	Checksum			

- Compression dictionary, if used, always comes before Checksum

- Note: encryption does not add any fields to the header

Decoding a header

Steps:

1. Verify that the magic bytes and version byte are correct.
   Exit the program if the bytes are incorrect.

2. Check which options are set in “flags”.
   That will determine the remaining bytes in the header, if any.

3. Pull out compression dictionary data (if enabled).

4. Pull out checksum value (if enabled).

Accessing individual bits

- There’s no native way in C to access individual bits of a byte

- Instead, you’ll need to use operations on the byte to pull out only the bit(s) you need
  - >>, <<, |, &, etc.

- See bit masking section of “Data Operations” lecture
  - Slides 55-58: https://drive.google.com/file/d/12OVVoRf0Uf-7DXLlTgY1ho3Qi9db05_h/view

Function: `parse_header()`

- Should parse the header from the input data
  - `input_data` is an array of bytes. You can access it with [ ]
- Configuration information should be written into the config struct
- Depending on the optional operations, some fields in the config struct may not be used at all
- `data_offset` field is the offset to the start of file data
  - It should equal the total number of bytes in the header
  - 4-byte header means `data_offset` should be 4

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- Header Format
- **Checksums**
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What is a checksum?

- Allows verification of file data integrity
  - If a byte in the file has changed, we can detect it!

- Concept
  - Some kind of hash of file data into a much smaller number
  - Process is repeatable and deterministic

- Integrity check: generate checksum twice
  - Once when “packing” the file. Record result in file header
  - Once when “unpacking” the file. Check against result in header
  - If they don’t match, file contents have changed!

Checksum implementation

- Unsigned 16-bit integer, initialized to zero
- Add every byte of the file data to it, one-by-one
    - Modular arithmetic occurs upon overflow

- Example
    - File data: 0x01, 0x03, 0x04
    - Checksum: 0x08

- If the checksum doesn't match when unpacking, the unpack tool should error and exit
    - This code is written for you in `unpack.c`

Function: `calculate_checksum()`

- Calculates a 16-bit unsigned checksum value over the input data
  - `input_data` is an array of bytes, you can access it with [ ]
  - `input_data` only contains data to calculate the checksum over, it does not contain header bytes

- Must not modify the input data

- Returns the calculated checksum value

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Basic stream cipher encryption

- Combine each individual byte of data with a random byte to encrypt it

1. Need some method for creating a series of random bytes
    - Must be deterministic based on some initial state (a password)

2. Need some operation for combining random bytes with data
    - XOR operation works well for this
    - To decrypt, just XOR against the random byte a second time

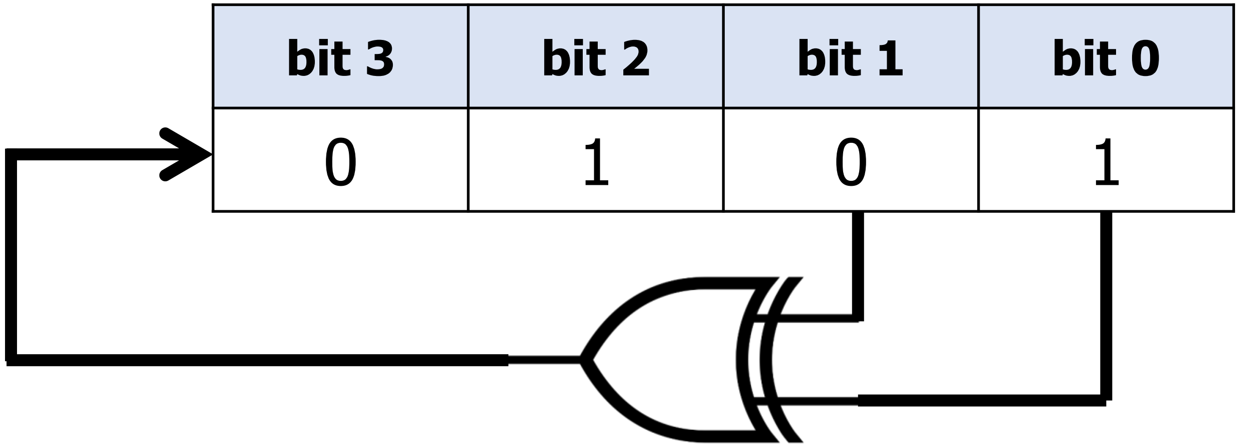
- Note: the method we’re using is insufficient to provide good security
    - Only 65535 possible starting states
    - Could be brute-forced to decrypt the file

Method for creating a pseudorandom byte stream

- Linear-Feedback Shift Register (LFSR)
  - Pattern of bit manipulations that is simple to implement in hardware/software
  - Creates sequences of bits that do not repeat for a very long time

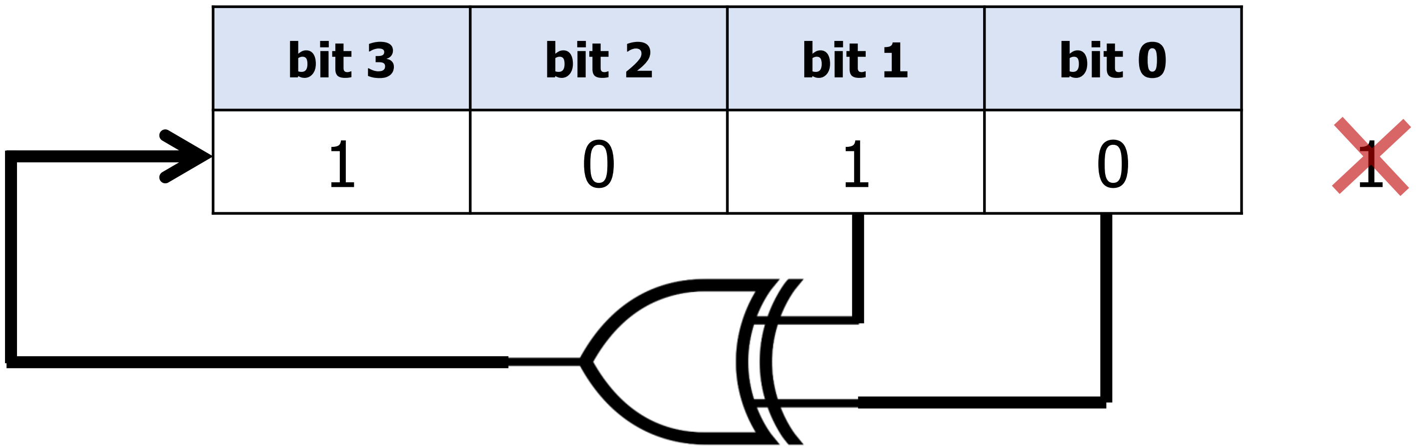
- LFSR takes in an input state and creates an output state
  - xors several bits together to create a new most-significant bit
  - Shifts all bits in state one to the right

Background: 4-bit LFSR example



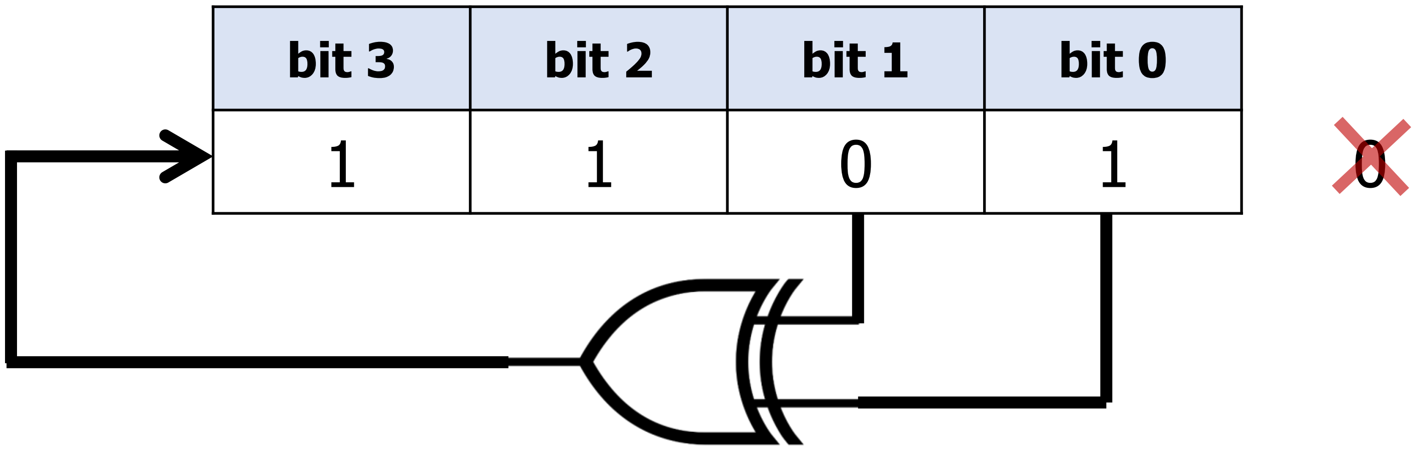
- Initial state: 0b0101

Background: 4-bit LFSR example, step 1



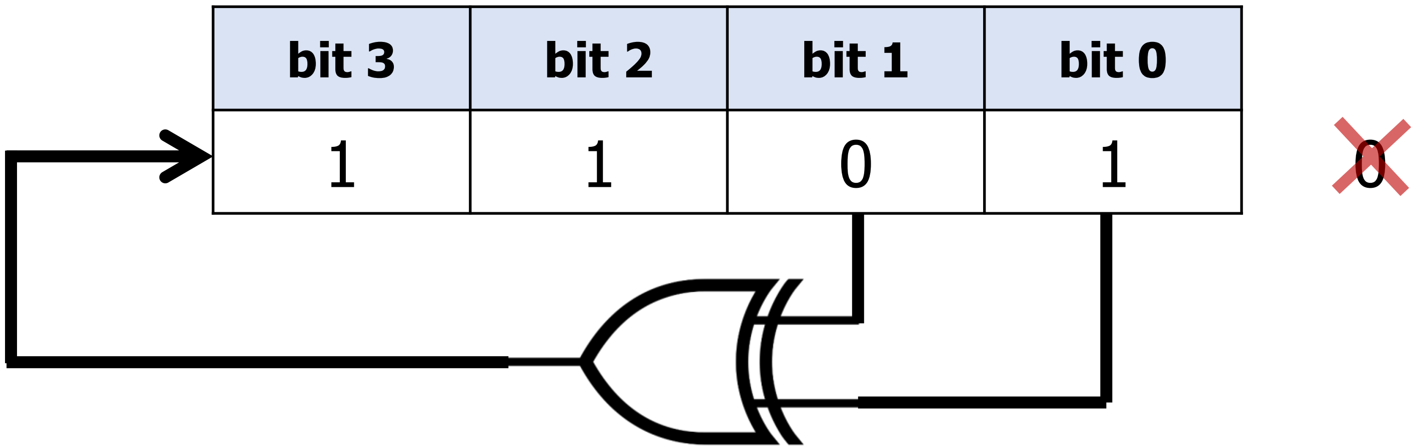
- Initial state: 0b0101
  - XOR of bits 0 and 1 = 1
  - Shift all bits right once, 0101 becomes 010
    - The former least-significant bit (1) is deleted
  - Set most-significant bit to xor result

Background: 4-bit LFSR example, step 2



- Initial state: 0b1010
  - XOR of bits 1 and 0 = 1
  - Shift all bits right once, 1010 becomes 101
    - The former least-significant bit (1) is deleted
  - Set most-significant bit to xor result

Background: 4-bit LFSR example, continued steps



- Next states:
  - 0b1110, 0b1111, 0b0111, 0b0011, 0b0001, 0b1000, 0b0100, 0b0010, 0b1001, 0b1100, 0b0110, 0b1011, 0b0101 (repeat!)
  - Iterates through 15 total states before repeating
    - Never hits 0b0000 (it would stick there permanently)

Background: 4-bit LFSR example

- Still feel like LFSRs don’t make sense?

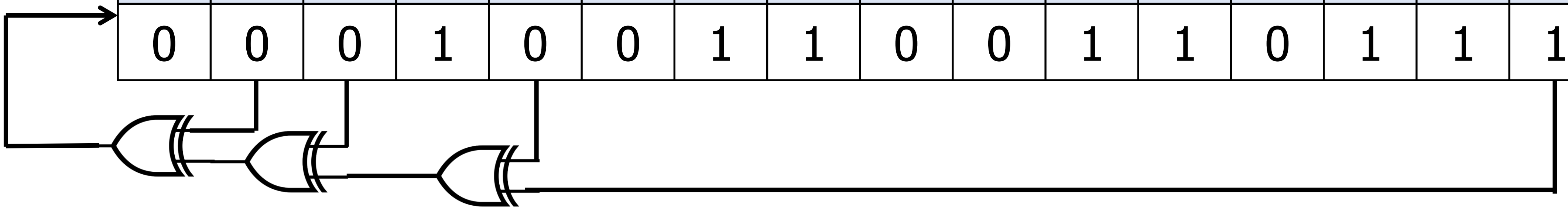
- Sometimes videos and animations can help!

- Here’s a youtube video our TA recommends: https://www.youtube.com/watch?v=1UCaZjdRC_c

Pack Lab LFSR design

- 16-bit LFSR
  - Accesses bits 0, 11, 13, and 14

bit 15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	bit 0
0	0	0	1	0	0	1	1	0	0	1	1	0	1	1	1



- Example initial state: 0x1337
  - XOR of bits: 1
  - Next state: 0b1000100110011011 -> 0x899B

Testing your LFSR

- We’ve provided some code for you that can test your LFSR implementation
  - Within `test-utilities.c`

1. LFSR should iterate in a known pattern
2. LFSR should hit all integers (except zero)

- If it’s not working, it can be annoying to debug
  - Check the bit pattern for the input and output and work it out on paper

Decrypting data

- Once you've implemented the LFSR, you can use it to generate 16-bit pseudorandom numbers
  - Each newstate returned is used as the pseudorandom number
  - Never use the encryption key as a pseudorandom number, always LFSR step first
- To encrypt data:
  - Generate a new LFSR state based on the previous state
  - XOR the LFSR state against the next two bytes of data in **little-endian** order
- Example: data=[0x60, 0x5A] and LFSR output 0x8016
  - 0x16 ^ 0x60 = 0x76
  - 0x80 ^ 0x5A = 0xDA
  - data = [0x76, 0xDA]

Initializing the LFSR

- The initial state for the LFSR is the encryption key
  - Then each iteration after that, the state is the previous output

- The encryption key is a 16-bit unsigned integer formed by running the checksum operation on the user's entered password

- Note: this is ALSO not very secure
  - There are many collisions where multiple passwords have the same value
  - Password "ab" checksums to the same value as password "ba"

Decryption edge case

- When decrypting, there may be an odd number of bytes in the file data!

- In that case, use the least-significant byte of the LFSR result, but not the most-significant byte
  - And then return from the decryption function

- Example: data=[0x60] and LFSR output 0x8016
  - 0x16 ^ 0x60 = 0x76
  - data = [0x76]
  - (do nothing with the most-significant byte from the LFSR)

Function: `lfsr_step()`

- Determines the next LFSR state given an initial state input
- Returns the new LFSR state

- Should not save state internally. To iterate through multiple LFSR states, use this function in some kind of loop
  - `state = lfsr_step(state);`

Function: `decrypt_data()`

- Decrypts the input data and writes result into output data
  - `input_data` is an array of bytes, you can access it with [ ]
  - `input_data` only contains data to decrypt, it does not contain header bytes

- Uses `lfsr_step()` to generate pseudorandom numbers for encryption
  - Initial state for the LFSR should be the encryption_key
  - The output state from the LFSR is used as both a random number and as the input state for the LFSR in the next iteration

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How do you make a file smaller?

- Compression is the act of making a file smaller
  - Files can get really large, so it would be nice to make them smaller
  - Actually, all of your pictures, music, and videos are compressed already

- Lossless compression means the process can be undone (decompression) and the output will exactly match the original input
  - Lossy compression is the other option, which is sometimes done for media
  - For example: delete the parts of the audio file that humans can't hear (MP3)

- We're going to use **lossless** compression
  - So the unpacked file should *exactly* match the original input file

Lossless compression algorithms

- There has been a lot of engineering put into compression algorithms
- One really good algorithm comes up with new bit encodings for each byte based on usage: Huffman Encoding
  - It's a little complex to implement though
- We will use a simpler algorithm: Run-length encoding

Run-length encoding concept

- Run-length encoding looks for repeated bytes and replaces them with an indication of how many times the byte repeated

- Conceptually: “aaaaabb” could turn into “five a’s and two b’s”
  - If there are enough repeated characters, this can save a lot of space!

- This kind of algorithm works really well on text files and raw image files

Pack Lab compression implementation

- We will use a version of run-length encoding where repeated bytes get replaced by a two-byte sequence
  - Specifies which byte and how many repeats

- Not all repeated bytes get reduced, we only reduce the 16 most-popular bytes in the file
  - The header contains a dictionary with the 16 most-popular bytes

Compression dictionary

- 16-byte array of uint8_t (unsigned bytes)

- Bytes are arranged in index order and are zero-indexed (0–15)

Byte offset	**0**	**1**	**2**	**3**
0	Magic: 0x0213		Version: 0x01	Flags
4	Dictionary[0]	Dictionary[1]	Dictionary[2]	Dictionary[3]
8	Dictionary[4]	Dictionary[5]	Dictionary[6]	Dictionary[7]
12	Dictionary[8]	Dictionary[9]	Dictionary[10]	Dictionary[11]
16	Dictionary[12]	Dictionary[13]	Dictionary[14]	Dictionary[15]

Special byte sequence

- When packing a file, if one of the 16 bytes in the dictionary appears twice or more in-a-row
  - Instead replace up to 15 repetitions with a special two-byte sequence
- First byte: “escape byte”
  - Signifies that this is a special sequence, not normal data
  - Always 0x07 which is unlikely to be used in text files at least
- Second byte:
  - Information about which dictionary character and how many repetitions

Normal case: repeated character

- First byte signals that something special is happening
- Second byte contains a 4-bit unsigned “repeat count”
- Followed by a 4-bit unsigned “dictionary index”

- Example: 0x0737
  - Three repetitions of dictionary entry 7

Bit	**bit 15**	**14**	**13**	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**bit 0**
Value	Escape Byte: 0x07								Repeat Count				Dictionary Index			

Special case: literal escape byte

- What if the file actually uses the byte value 0x07?

- Special case: if the first byte is 0x07 and the second byte is 0x00
  - Then the output should be a single byte: 0x07

- Any other pattern with a "repeat count" of zero is invalid

Bit	bit 15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	bit 0
Value	Escape Byte: 0x07								Literal Escape Byte: 0x00							

Decompression example

- Input data: {0x01, 0x07, 0x42}
- Dictionary: {0x30, 0x31, 0x32, 0x33 …} (didn't write the rest due to space)

- Resulting output data: {0x01, 0x32, 0x32, 0x32, 0x32}

- Explanation
  - First byte isn't special and just gets copied over
  - Second byte is the escape byte, which means the third byte holds a repeat count (4) and dictionary index (2)
    - So the output should be four copies of `dictionary[2]` (0x32)

Implementation guide

- Iterate through bytes in the input
  - Either it’s a normal byte
  - Or it’s an escape character

- For normal bytes, just copy them over to the output
- For special bytes, read the second byte and determine what to do
  - Either multiple repetitions of a dictionary byte
  - Or a single literal escape byte

- Be careful to not go past the end of the input!
  - Check against lengths as you go

Function: `decompress_data()`

- Decompresses the input data and writes the result into output data
  - `dictionary_data` is the compression dictionary used when compressing the data
  - `input_data` is an array of bytes, you can access it with [ ]
  - `input_data` only contains data to decrompress, it does not contain header bytes

- Returns the total length of the decompressed data

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- **Testing**

Testing overview

1. Write tests in `test-utilities.c`

2. You can pack your own files using the `pack` application

3. We have provided some example packed files, and their original versions, in the `example_files/` directory

4. There are some other useful tools you should know about for looking at files
    - `xxd` and `diff`

Testing your utility function implementations

- Each operation takes in an array of data
- You can craft your own array of unsigned 8-bit data and pass it into the function
- This is much easier than crafting full files files to unpack

Using the Pack application

```
./pack [-cek] inputfilename outputfilename
```

- -c: Optionally compresses the file
- -e: Optionally encrypts the (compressed) file with a password
- -k: Optionally checksums the (compressed & encrypted) file

- The three options can be combined in any way
  - -e: Encryption only
  - -ck: Compression and Checksum
  - -cek: Compression, Encryption, and Checksum
  - no flags: Add header, but perform no operations

Example packed files

- Original and packed versions of some files have been provided to you in the `example_files/` directory

- Each fits the pattern of filename.options.pack
  - Where options are
    - c – compress
    - e – encrypt
    - k – checksum

  - The password for any encrypted file is: cs213

Other useful tools – seeing raw hex values inside a file

- `xxd filename`
  - Dumps raw hex values of the file

- Format:
  - On the left are addresses starting at 0x00000000
  - In the middle are the hexadecimal values
  - On the right are the same values interpreted as an ASCII encoding
  - Example:

```
[brghena@ubuntu example_files] [main *] $ xxd long_file.txt
00000000: 6161 6161 6161 6161 6161 6161 6161 6161  aaaaaaaaaaaaaaaa
00000010: 3162 6262 6363 6364 6464 6565 6566 6666  1bbbcccdddeeefff
00000020: 6767 6768 6868 6969 696a 6a6a 6b6b 6b6c  ggghhhiiijjjkkkl
00000030: 6c6c 6d6d 6d6e 6e6e 6f6f 6f70 7070 7171  llmmmnnnooopppqq
00000040: 7172 7272 7373 7374 7474 7575 7576 7676  qrrrssstttuuuvvv
00000050: 7777 7778 7878 7979 797a 7a7a 0a         wwwxxxyyyzzz.
```

Ways to use xxd

- `xxd filename | head -2`
  - Only show the first ten lines of hexadecimal output for a file
  - Useful for looking at the header bytes of a file

- `xxd filename > filename.hex`
  - Convert a normal file into hexadecimal

- `xxd -r filename.hex > filename`
  - Convert hexadecimal back into a normal file
  - Can do this after editing some bytes in the hex to craft your own input

Other useful tools – checking for differences in files

- `diff filename1 filename2`
  - Checks for differences between two files
  - Doesn't output anything if they match
  - Useful for determining if an unpacked file matches the original file

- If the two files do differ:
  - For text files, it will show you the text that's different
  - For raw binary files, it will just say that they differ

  - To see the difference for binary files, convert both into .hex files and then diff those!