Chapter 3: Programming
Compiler

- An interpreter takes a program as input and makes it happen.
- A compiler takes a program as input and creates a machine-language program as output.
- A program that converts a program into a program—*twisted*, but useful!
Game Plan

• We’ll develop two schemes that compute the value of the expression.
  ‣ One leaves the final value in “acc”.
  ‣ The other leaves it in a variable in memory.
• Both are given a list of variables they can use for temporary storage.
• Mutually recursive (oooh).
Code Generation: Var

- Expression: A

\[
\begin{align*}
\text{answer in acc} & \quad \text{answer in P} \\
\text{acc} &= A & \text{acc} &= A \\
& \quad \text{P} = \text{acc}
\end{align*}
\]
Code Generation: not

• Expression: not EXPR

answer in acc (temp N)

generate code for

EXPR, answer in N

acc = not N

answer in P

generate code for

EXPR, answer in acc

P = not acc

• Note: We keep a pool of temporary variables to use as needed (not just N).
Code Generation: or

- Expression: \((\text{EXPR}_1 \text{ or } \text{EXPR}_2)\)

\[
\begin{align*}
\text{answer in acc (temp } N) \\
generate code for \text{EXPR}_1, \text{ answer in } N \\
generate code for \text{EXPR}_2, \text{ answer in acc} \\
acc = acc \text{ or } N
\end{align*}
\]

\[
\begin{align*}
\text{answer in } P \\
generate code for \text{EXPR}_1, \text{ answer in } P \\
generate code for \text{EXPR}_2, \text{ answer in acc} \\
P = acc \text{ or } P
\end{align*}
\]

- Note: “and” is handled the same way.
Example Expression

- Expression: not A or B

\[
\text{answer in acc} \\
\text{generate code for} \\
\text{not A, answer in } N
\]

\[
\text{generate code for} \\
\text{B, answer in acc} \\
\text{acc = acc or } N
\]

\[
\text{answer in P} \\
\text{generate code for} \\
\text{not A, answer in } P
\]

\[
\text{generate code for} \\
\text{B, answer in acc} \\
P = \text{acc or } P
\]
Example Expression

- Expression: not A or B

\[
\text{answer in acc} \quad \text{generate code for} \\
\text{not A, answer in } N \\
\text{generate code for} \\
\text{A, answer in acc} \\
\]

\[
N = \text{not acc} \\
\text{generate code for} \\
B, \text{answer in acc} \\
\text{acc = acc or N} \\
\]

- answer in P
- generate code for
- not A, answer in P

\[
\text{generate code for} \\
B, \text{answer in acc} \\
P = \text{acc or P} \\
\]
Example Expression

- Expression: \( \text{not } A \text{ or } B \)

\[
\begin{align*}
\text{answer in acc} & \\
\text{generate code for} & \\
\text{not } A, \text{ answer in } N & \\
\text{generate code for} & \\
A, \text{ answer in acc} & \\
\text{acc} &= A \\
N &= \text{not acc} & \\
\text{generate code for} & \\
B, \text{ answer in acc} & \\
\text{acc} &= \text{acc or } N & \\
\text{or} & \\
\text{not} & \\
B & \\
\text{P} &= \text{acc or } P
\end{align*}
\]
Example Expression

- Expression: not A or B

```
answer in acc
generate code for
not A, answer in N

generate code for
A, answer in acc
acc = A
N = not acc
generate code for
B, answer in acc
acc = B
acc = acc or N
```

```
answer in P
generate code for
not A, answer in P

generate code for
B, answer in acc
P = acc or P
```
Example Expression

- Expression: not A or B

answer in acc
generate code for not A, answer in N
generate code for A, answer in acc
acc = A
N = not acc
generate code for B, answer in acc
acc = B
acc = acc or N

or

not

A

answer in P
generate code for not A, answer in P
generate code for A, answer in acc
P = not acc
generate code for B, answer in acc
P = acc or P
Example Expression

- Expression: not A or B

answer in acc

- generate code for not A, answer in N
  - generate code for A, answer in acc
    - acc = A
    - N = not acc
    - generate code for B, answer in acc
      - acc = B
      - acc = acc or N

answer in P

- generate code for not A, answer in P
  - generate code for A, answer in acc
    - acc = A
    - P = not acc
    - generate code for B, answer in acc
      - acc = B
      - P = acc or P
Example Expression

• Expression: not A or B

- answer in acc
  - generate code for not A, answer in N
    - generate code for A, answer in acc
      - acc = A
      - N = not acc
      - generate code for B, answer in acc
      - acc = B
      - acc = acc or N

- answer in P
  - generate code for not A, answer in P
    - generate code for A, answer in acc
      - acc = A
      - P = not acc
      - generate code for B, answer in acc
      - acc = B
      - P = acc or P
Assembler

- An assembler handles the last little step of translating the series of instructions to a series of numbers.

<table>
<thead>
<tr>
<th>answer in acc</th>
<th>answer in P</th>
</tr>
</thead>
<tbody>
<tr>
<td>acc = A</td>
<td>acc = A</td>
</tr>
<tr>
<td>N = not acc</td>
<td>P = not acc</td>
</tr>
<tr>
<td>acc = B</td>
<td>acc = B</td>
</tr>
<tr>
<td>acc = acc or N</td>
<td>P = acc or P</td>
</tr>
<tr>
<td></td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>127</td>
</tr>
<tr>
<td></td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>79</td>
</tr>
</tbody>
</table>
Inefficiency

• (not A or B)

• Automatically generated machine code:

  answer in acc
  acc = A 32
  N = not acc 125
  acc = B 33
  acc = acc or N 13

• By hand: answer in acc
  acc = not A 48
  acc = acc or B 1

• Often more than one way to do it!
Many ways of speeding up compiled code have been developed.

Want to minimize steps, temporary variables.

I’ll describe two important ones:

- Shared subexpressions
- Logical equivalence
Automatic Code (13 inst.)

- $E = ((A \text{ and } B) \text{ and } C) \text{ or } ((A \text{ and } B) \text{ and } D)$
  - $E = (A \text{ and } B) \text{ and } C$
    - $E = A \text{ and } B$
      - acc = A
      - acc = B
      - $E = acc \text{ and } E$
      - acc = C
        - $E = acc \text{ and } E$
  - $E = A \text{ and } B$
    - acc = A
    - acc = B
    - $E = acc \text{ and } E$
    - acc = C
      - $E = acc \text{ and } E$

- $acc = (A \text{ and } B) \text{ and } D$
  - $N = A \text{ and } B$
    - acc = A
    - N = acc
    - acc = B
      - $N = acc \text{ and } N$
      - acc = D
    - acc = acc and N
  - $E = acc \text{ or } E$

- 1 temps, 13 instructions
Shared Subexpression

- \( E = ( (A \text{ and } B) \text{ and } C) \text{ or } ( (A \text{ and } B) \text{ and } D) \)
  
  - \( N = A \text{ and } B \)
    
    - \( N = A \)
      
      - acc = A
    
    - acc = B
    
    - \( N = N \text{ and } acc \)
  
  - \( E = (N \text{ and } C) \text{ or } (N \text{ and } D) \)
    
    - \( E = N \text{ and } C \)
      
      - acc = N

- 2 temps, 13 instructions
Logical Equivalence

- $E = ((A \text{ and } B) \text{ and } C) \text{ or } ((A \text{ and } B) \text{ and } D)$

- $E = (A \text{ and } B) \text{ and } (C \text{ or } D)$

- $E = A \text{ and } B$
- acc = A
- $E = acc$
- acc = B
- $E = E \text{ and } acc$
- acc = C or D
- acc = C

- N = acc
- acc = D
- acc = acc or N
- $E = E \text{ and } acc$

- 1 temps, 9 instructions
A Compiler

- A program that translates computer programs that people write into a machine language instructions for the computer to execute.

(Adapted from notes by Barbara Ryder.)
Interpreters

- *Compiler* translates program to machine lang.
- *Interpreter* translates statements by executing equivalent commands
  - No real translation step
- Interpretation requires programming language have a defined meaning for its statements—*semantics*
  - Sometimes defined mathematically, sometimes in English.
## Recap: Reduction

<table>
<thead>
<tr>
<th>Level</th>
<th>Examples</th>
<th>Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>software libraries</td>
<td>graphics, animation, robotics</td>
<td>networking, security, mathematics</td>
</tr>
<tr>
<td>high-level language</td>
<td>Python</td>
<td>C, Java, C++, Logo, LISP, Fortran, ML</td>
</tr>
<tr>
<td>machine language</td>
<td>ML$^3$</td>
<td>x86, CARDIAC, Z80</td>
</tr>
<tr>
<td>logic gates</td>
<td>equal, ifthenelse, add</td>
<td>memlookup, memwrite</td>
</tr>
<tr>
<td>basic logic gates</td>
<td>and, or, not</td>
<td>nor, nand, xor</td>
</tr>
<tr>
<td>physical bits</td>
<td>0,1 via high/low voltage</td>
<td>water pressure, kinetic energy</td>
</tr>
</tbody>
</table>
Does It End There?

• Of course not.

• We can continue to build sophisticated programs out of simpler programs.

• The idea of subroutines (procedures, functions) makes this work.
A lot of research in computer science is about designing and creating just the right set of subroutines, sometimes called libraries.

You don’t have enough background yet to weigh in on these problems.

But, there is an analogous set of problems where you are already an expert...
Gilligan’s Island Theme

Just sit right back and you'll hear a tale, a tale of a fateful trip. That started from this tropic port, aboard this tiny ship. The mate was a mighty sailin' man, the skipper brave and sure. Five passengers set sail that day, for a three hour tour, a three hour tour… The weather started getting rough, the tiny ship was tossed. If not for the courage of the fearless crew, the Minnow would be lost; the Minnow would be lost. The ship took ground on the shore of this uncharted desert isle, with Gilligan, the Skipper too, the Millionaire, and his Wife, the Movie Star, the Professor and Mary Ann, here on Gilligan's Isle.
when Sprite1 clicked
play sound "Just sit right back"
wait 6 secs
play sound "That started from"
wait 4 secs
play sound "The mate was a"
wait 11 secs
play sound "The weather started"
wait 12 secs
play sound "The ship set ground"
wait 13 secs
play sound "The movie star"
wait 8 secs
stop all sounds
Chorus Structure

Clementine

In a cavern, in a canyon,
Excavating for a mine,
Dwelt a miner forty niner,
And his daughter Clementine.

Oh my darling, oh my darling,
Oh my darling, Clementine!
Thou art lost and gone forever
Dreadful sorry, Clementine.

Light she was and like a fairy,
And her shoes were number nine,
Herring boxes, without topses,
Sandals were for Clementine.

Oh my darling, oh my darling,
Oh my darling, Clementine!
Thou art lost and gone forever
Dreadful sorry, Clementine.

Drove she ducklings to the water
Ev'ry morning just at nine,
Hit her foot against a splinter,
Fell into the foaming brine.

Oh my darling, oh my darling,
Oh my darling, Clementine!
Thou art lost and gone forever
Dreadful sorry, Clementine.

Ruby lips above the water,
Blowing bubbles, soft and fine,
But, alas, I was no swimmer,
So I lost my Clementine.

How I missed her! How I missed her,
How I missed my Clementine,
But I kissed her little sister,
I forgot my Clementine.

Oh my darling, oh my darling,
Oh my darling, Clementine!
Thou art lost and gone forever
Dreadful sorry, Clementine.
Scratch Code

when Miner clicked

play sound In a cavern, in a and wait
play sound Dwelt a miner and wait
play sound Oh my darlin', oh and wait
play sound Thou art lost and and wait
play sound Light she was and and wait
play sound Herring boxes and wait
play sound Oh my darlin', oh and wait
play sound Thou art lost and and wait
play sound Drove she ducklings and wait
play sound Hit her foot against and wait

play sound Oh my darlin', oh and wait
play sound Thou art lost and and wait
play sound Ruby lips above the and wait
play sound But, alas, I was no and wait
play sound Oh my darlin', oh and wait
play sound Thou art lost and and wait
play sound How I missed her! and wait
play sound But I kissed my little and wait
play sound Oh my darlin', oh and wait
play sound Thou art lost and and wait
when Miner clicked

play sound In a cavern, in a ▼ and wait
play sound Dwelt a miner ▼ and wait
play sound Oh my darlin', oh ▼ and wait
play sound Thou art lost and ▼ and wait
play sound Light she was and ▼ and wait
play sound Herring boxes ▼ and wait
play sound Oh my darlin', oh ▼ and wait
play sound Thou art lost and ▼ and wait
play sound Drove she ducklings ▼ and wait
play sound Hit her foot against ▼ and wait

play sound Oh my darlin', oh ▼ and wait
play sound Thou art lost and ▼ and wait
play sound Ruby lips above the ▼ and wait
play sound But, alas, I was no ▼ and wait
play sound Oh my darlin', oh ▼ and wait
play sound Thou art lost and ▼ and wait
play sound How I missed her! ▼ and wait
play sound But I kissed my little ▼ and wait
play sound Oh my darlin', oh ▼ and wait
play sound Thou art lost and ▼ and wait
A Subroutine

**Now, “Chorus” is its own little program, or a new statement in the language, that we can call whenever we need it.**

**Calling the subroutine does all the steps, then the program resumes from where the call took place.**

**Simplifies the program, easier to maintain, extend, fix.**
All My Loving
Lennon/McCartney

Close your eyes and I’ll kiss you,
Tomorrow I’ll miss you,
Remember I’ll always be true,
And then while I’m away,
I’ll write home every day,
And I’ll send all my loving to you.
I’ll pretend I am kissing,
The lips I am missing,
And hope that my dreams will come true,
And then while I’m away,
I’ll write home every day,
And I’ll send all my loving to you.
All my loving, I will send to you,
All my loving, darling, I’ll be true.
Close your eyes and I’ll kiss you,
Tomorrow I’ll miss you,
Remember I’ll always be true,
And then while I’m away,
I’ll write home every day,
And I’ll send all my loving to you.
All my loving, I will send to you,
All my loving, darling, I’ll be true.
All my loving. All my loving
Woo, all my loving, I will send to you

What subroutines would you define?
All My Loving
Lennon/McCartney

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All my loving. All my loving
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All my loving, darling, I'll be true.

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Tomorrow I'll miss you,
Remember I'll always be true,
And then while I'm away,
I'll write home every day,
And I'll send all my loving to you.

All my loving, I will send to you,
All my loving, darling, I'll be true,
All my loving. All my loving
Woo, all my loving, I will send to you
Shared Structure

All My Loving
Lennon/McCartney

Close your eyes and I'll kiss you,
Tomorrow I'll miss you,
Remember I'll always be true,
And then while I'm away,
I'll write home every day,
And I'll send all my loving to you.

I'll pretend I am kissing,
The lips I am missing,
And hope that my dreams will come true,
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All my loving, I will send to you,
All my loving, darling, I'll be true.

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I'll write home every day,
And I'll send all my loving to you.
All my loving, I will send to you,
All my loving, darling, I'll be true.

Woo, all my loving, I will send to you
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All my loving, I will send to you,
All my loving, darling, I'll be true.

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The lips I am missing,
And hope that my dreams will come true,
And then while I'm away,
I'll write home every day,
And I'll send all my loving to you.
All my loving, I will send to you,
All my loving, darling, I'll be true.
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And I'll send all my loving to you.
All my loving, I will send to you,
All my loving, darling, I'll be true,
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Lennon/McCartney

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And then while I'm away,
I'll write home every day,
And I'll send all my loving to you.

I'll pretend I am kissing,
The lips I am missing,
And hope that my dreams will come true,
And then while I'm away,
I'll write home every day,
And I'll send all my loving to you.

All my loving, I will send to you,
All my loving, darling, I'll be true.

Close your eyes and I'll kiss you,
Tomorrow I'll miss you,
Remember I'll always be true,
And then while I'm away,
I'll write home every day,
And I'll send all my loving to you.

All my loving, I will send to you,
All my loving, darling, I'll be true,
All my loving, I will send to you.
**Eight Days a Week (Beatles)**

Ooh I need your love babe, guess you know it’s true,
Hope you need my love babe just like I need you,

Hold me, love me,
Hold me, love,
Ain’t got nothin’ but love babe,
Eight days a week.

Love you ev’ry day girl, always on my mind,
One thing I can say girl, love you all the time,

Hold me, love me,
Hold me, love me,
Ain’t got nothin’ but love babe,
Eight days a week.

Eight days a week I love you,
Eight days a week is not enough to show I care.

Hold me, love me,
Hold me, love me,
Ain’t got nothin’ but love babe,
Eight days a week.

Eight days a week. Eight days a week.

Ooh I need your love babe, guess you know it’s true,
Hope you need my love babe just like I need you,
Eight Days a Week (Beatles)

Ooh I need your love babe, guess you know it’s true,
Hope you need my love babe just like I need you,
Hold me, love me,
Hold me, love,
Ain’t got nothin’ but love babe,
Eight days a week.

Hold me, love me,
Hold me, love,
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Love you ev’ry day girl, always on my mind,
One thing I can say girl, love you all the time,

Hold me, love me,
Hold me, love,
Ain’t got nothin’ but love babe,
Eight days a week.

Eight days a week I love you,
Eight days a week is not enough to show I care.

Hold me, love me,
Hold me, love me,
Ain’t got nothin’ but love babe,
Eight days a week.

Eight days a week. Eight days a week.
Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a cow, E-I-E-I-O
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"
Old Macdonald had a farm, E-I-E-I-O
Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a pig, E-I-E-I-O
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"
Old Macdonald had a farm, E-I-E-I-O
Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a horse, E-I-E-I-O
With a "neigh, neigh" here and a "neigh, neigh" there
Here a "neigh" there a "neigh"
Everywhere a "neigh-neigh"
With a (snort) here and a (snort) there
Here a (snort) there a (snort).
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"
Old Macdonald had a farm, E-I-E-I-O
Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a chick, E-I-E-I-O
With a "cluck, cluck" here and a "cluck, cluck" there
Here a "cluck" there a "cluck"
Everywhere a "cluck-cluck"
With a "neigh, neigh" here and a "neigh, neigh" there
Here a "neigh" there a "neigh"
Everywhere a "neigh-neigh"
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"
Old Macdonald had a farm, E-I-E-I-O
Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a cow, E-I-E-I-O
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a pig, E-I-E-I-O
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"
Old Macdonald had a farm, E-I-E-I-O

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a horse, E-I-E-I-O
With a "neigh, neigh" here and a "neigh, neigh" there
Here a "neigh" there a "neigh"
Everywhere a "neigh-neigh"

With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Old Macdonald had a farm, E-I-E-I-O  
And on his farm he had a cow, E-I-E-I-O  
With a "moo-moo" here and a "moo-moo" there  
Here a "moo" there a "moo"  
Everywhere a "moo-moo"  

Old Macdonald had a farm, E-I-E-I-O  
And on his farm he had a pig, E-I-E-I-O  
With a (snort) here and a (snort) there  
Here a (snort) there a (snort)  
Everywhere a (snort-snort)  
With a "moo-moo" here and a "moo-moo" there  
Here a "moo" there a "moo"  
Everywhere a "moo-moo"  
Old Macdonald had a farm, E-I-E-I-O  

Old Macdonald had a farm, E-I-E-I-O  
And on his farm he had a horse, E-I-E-I-O  
With a "neigh, neigh" here and a "neigh, neigh" there  
Here a "neigh" there a "neigh"  
Everywhere a "neigh-neigh"  
With a (snort) here and a (snort) there  
Here a (snort) there a (snort)  
Everywhere a (snort-snort)  
With a "moo-moo" here and a "moo-moo" there  
Here a "moo" there a "moo"  
Everywhere a "moo-moo"  
Old Macdonald had a farm, E-I-E-I-O
Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a cow, E-I-E-I-O
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a pig, E-I-E-I-O
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
Everywhere a "moo-moo"

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a horse, E-I-E-I-O
With a "neigh, neigh" here and a "neigh, neigh" there
Here a "neigh" there a "neigh"
Everywhere a "neigh-neigh"

With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a cow, E-I-E-I-O
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a pig, E-I-E-I-O
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a horse, E-I-E-I-O
With a "neigh, neigh" here and a "neigh, neigh" there
Here a "neigh" there a "neigh"
Everywhere a "neigh-neigh"

Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"
Old Macdonald had a farm, E-I-E-I-O

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a chick, E-I-E-I-O
With a "cluck, cluck" here and a "cluck, cluck" there
Here a "cluck" there a "cluck"
Everywhere a "cluck-cluck"
With a "neigh, neigh" here and a "neigh, neigh" there
Here a "neigh" there a "neigh"
Everywhere a "neigh-neigh"
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"
Old Macdonald had a farm, E-I-E-I-O
Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a cow, E-I-E-I-O
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"
Old Macdonald had a farm, E-I-E-I-O

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a pig, E-I-E-I-O
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"
Old Macdonald had a farm, E-I-E-I-O

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a horse, E-I-E-I-O
With a "neigh, neigh" here and a "neigh, neigh" there
Here a "neigh" there a "neigh"
Everywhere a "neigh-neigh"
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"
Old Macdonald had a farm, E-I-E-I-O

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a chick, E-I-E-I-O
With a "cluck, cluck" here and a "cluck, cluck" there
Here a "cluck" there a "cluck"
Everywhere a "cluck-cluck"
With a "neigh, neigh" here and a "neigh, neigh" there
Here a "neigh" there a "neigh"
Everywhere a "neigh-neigh"
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"
Old Macdonald had a farm, E-I-E-I-O
Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a cow, E-I-E-I-O
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a pig, E-I-E-I-O
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a horse, E-I-E-I-O
With a "neigh, neigh" here and a "neigh, neigh" there
Here a "neigh" there a "neigh"
Everywhere a "neigh-neigh"
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a chick, E-I-E-I-O
With a "cluck, cluck" here and a "cluck, cluck" there
Here a "cluck" there a "cluck"
Everywhere a "cluck-cluck"
With a "neigh, neigh" here and a "neigh, neigh" there
Here a "neigh" there a "neigh"
Everywhere a "neigh-neigh"
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"
Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a cow, E-I-E-I-O

With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"

Old Macdonald had a farm, E-I-E-I-O

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a pig, E-I-E-I-O
With a (snort) here and a (snort) there

Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"

Old Macdonald had a farm, E-I-E-I-O

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a horse, E-I-E-I-O
With a "neigh, neigh" here and a "neigh, neigh" there

Here a "neigh" there a "neigh"
Everywhere a "neigh-neigh"
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"

Old Macdonald had a farm, E-I-E-I-O

Old Macdonald had a farm, E-I-E-I-O
And on his farm he had a chick, E-I-E-I-O
With a "cluck, cluck" here and a "cluck, cluck" there
Here a "cluck" there a "cluck"
Everywhere a "cluck-cluck"
With a "neigh, neigh" here and a "neigh, neigh" there
Here a "neigh" there a "neigh"
Everywhere a "neigh-neigh"
With a (snort) here and a (snort) there
Here a (snort) there a (snort)
Everywhere a (snort-snort)
With a "moo-moo" here and a "moo-moo" there
Here a "moo" there a "moo"
Everywhere a "moo-moo"

Old Macdonald had a farm, E-I-E-I-O
But Notice...

• Each time we “snort”, we follow it with “moo”.
• Each time we “neigh”, we follow it with “snort”.
• Each time we “cluck”, we follow it with “neigh”.
• Let’s put the earlier noises into the later subroutines...
At the highest level, the song consists of one verse per animal.
Cow

- Needs to know two things
  - Sing the verse
  - Sing the animal sounds (and highlight)
Pig

- Animal-sound subroutine oinks
  - then calls the cow’s sound to finish the verse!
Horse

- Animal-sound subroutine neighs
  - then calls the pig’s sound
    - which calls the cow’s sound to finish the verse!
Chick

- Animal-sound subroutine clucks
  - then calls the horse’s sound
    - which calls the pig’s
    - which calls the cow’s to finish the verse!
Subroutines So Far

- Can be used to gather up repeated code in one place.
- Can be deeply nested to capture structure when necessary.
- Next, parameters greatly increase the power of the subroutine idea...
Magical Mystery Tour (Beatles)

Roll up, roll up for the mystery tour.
Roll up, roll up for the mystery tour.
Roll up, roll up for the mystery tour.
Roll up, roll up for the mystery tour.
The magical mystery tour is ___ waiting to take you away, ___ waiting to take you away.

Roll up, roll up for the mystery tour.
Roll up, roll up for the mystery tour.
Roll up, roll up for the mystery tour.
Roll up, roll up for the mystery tour.
The magical mystery tour is ___ hoping to take you away, ___ hoping to take you away.

Roll up, roll up for the mystery tour.
Roll up, roll up for the mystery tour.
Roll up, roll up for the mystery tour.
Roll up, roll up for the mystery tour.
The magical mystery tour is ___ coming to take you away, ___ coming to take you away.
The magical mystery tour is ___ dying to take you away, ___ dying to take you away, take you today.

- Verse structure is nearly repetitive. Can’t quite define a single subroutine that covers all three.
- If we could fill in the blank, we could reuse the same routine...
In The Verse...

- Plug in the word at the proper time.
Main Song

- Do each verse with a different setting of “word”.
- Then, sing the conclusion.
Recursion...

- We saw in McDonald and other examples that subroutines can call other subroutines.
- Sometimes it is useful for a subroutine to call itself.
- This is called recursion.
- First, some song examples, then more general...
A Recursive Song!

- Sing a verse
- Update bottles
- Sing the next verse
• Some people think recursion is scary, but it’s all around us: language, nature, toys, music, family trees, mathematical expressions.

• If you like self-reference, you’ll love recursion!
Some people think recursion is scary, but it’s all around us: language, nature, toys, music, family trees, mathematical expressions.

If you like self-reference, you’ll love recursion!
This is 'The Song That Doesn't End'
Yes it goes on, and on my friend
Some people, started singing it
not knowing what it was
And they’ll just keep on singing it
forever just because...
This is 'The Song That Doesn't End'
Yes it goes on, and on my friend
Some people, started singing it
not knowing what it was
And they’ll just keep on singing it
forever just because...

- Featured in “Lambchop’s Play-along”
This is 'The Song That Doesn't End' Yes it goes on, and on my friend Some people, started singing it not knowing what it was And they’ll just keep on singing it forever just because...

- Featured in “Lambchop’s Play-along”
- Canceled.