

## 1 Yet to Do

There's a long list of things wrong with this. It's semi-usable, but here's a list of things to revisit (or visit).

- The way tabs work with windows – drag & drop, and the way the data for each tab is associated with internal data structures.
- Allow user to specify font size (and maybe the font, although any sane person will want a mono-spaced font).
- The line numbers are buggy. They work, but can be misaligned until you scroll.
- The basic framework for wizard code is there, but no more than the framework. In particular, the means of outputting more types of **Statement** needs to be fleshed out.
- Certain wizards (like Bezier curves) should have a UI specific to them. Other UIs might be handy too (bolt circles), but are less necessary. None of these wizards exist yet in any form.
- The “machine setup” wizard framework is also minimal. This is for things like specifying the tool table, work offsets table, billet dimensions, etc.
- Exception handling could be improved. It's minimally typed for one thing.
- Go through the code and explain (in this document) how each transformation takes place. There are edge cases that might surprise the user. Some of the more detailed calculations belong in the developer's manual.
- There is no 3D rendering at all.

## 2 G-Code

There is no universally accepted standard for “G-code.” The most commonly used codes do adhere to common usage, but usage for the less common codes varies from one CNC controller to the next. GER assumes that the common codes do follow a certain form; for other codes, how they are dealt with is left up to the user.

GER is more flexible than many real-world controllers about the order and grouping of codes. For instance, something like this is accepted:

```
G01 X1.0 G21 G01 Y250.0
```

and would be interpreted as

```
G01 X1.0  
G21  
G01 Y250.0
```

Statements may be terminated by either a new-line (*i.e.*, a “carriage return” or “enter”), or by a semi-colon. Thus,

```
G01 X1.0; Y2.0
```

is valid and means something entirely different than

```
G01 X1.0 Y2.0
```

If it is possible for *you* to make sense of your program by reading the codes one chunk at a time, then the simulator can probably make sense of it too, although the controller of an actual machine may be more strict or may have a different interpretation.

Which leads to the next point. GER is both a simulator and a translator. As a simulator, it can be used to view a 3D rendering of the part generated by the G-code, or it can be used to translate complex or idiosyncratic code to something simpler that will be accepted by a wide variety of machines. For example, M47 (repeat program) doesn’t make sense when simulating, and is definitely not a standard code, but it may be important to pass that command through when translating because it’s useful on the physical machine.

For uncommon codes, GER assumes that the code extends to the end of the line on which it appears (or to a semi-colon). GER can’t know the idiosyncracies of every machine, so these uncommon codes simply pass through the translator so that they can be fed to a physical machine that may understand them. By default, the GER simulator ignores these codes. For something like M08 or M09 (coolant on/off), ignoring the code is a natural choice; but in other cases, like G84.3 (a left-handed tapping cycle), it is possible to define the code’s meaning so that GER can simulate it faithfully. See SOME-FUTURE-SECTION.

In addition to the ability to define uncommon codes, it is also possible to define your own functions that act as “wizards.” For example, one might define

```
Pocket 75.0 30.0 10.0
```

to cut a pocket 10mm deep, measuring 75mm by 30mm. How to define these wizards will be discussed below (WHERE?). In particular, wizard commands must start with two consecutive letters.

### 3 Common Codes

The codes described below are common enough to assume that they take a standard form and have a standard meaning. For any codes not on this list, GER assumes that the full statement runs to the end-of-line or the next semi-colon.

The table below is organized by “statement,” meaning a series of inputs that makes sense together. To make the descriptions more concise, [...] is used for an optional term, *n* means a number, possibly with a decimal, and *w* means a whole number. What appears below is a quick summary; the individual codes are described in more detail later.

<i>Move</i>	<code>[X<math>n</math>] [Y<math>n</math>] [Z<math>n</math>] [F<math>n</math>]</code>
	Notice the use of [ and ]: each of these terms is optional. This command moves the tool along a line segment to the given X, Y, Z, at the given feed rate. When in rapid mode (G00), F is not allowed. Once a feed rate is given, it will be used in G01-mode until the feed rate is changed.
G00	Rapid travel mode. The program begins in rapid travel mode. If the very first line is X1.000 Y1.000, then the tool will move to that position in rapid mode.
G01	Ordinary (not rapid) travel mode.
G02	Clockwise arc.
G03	Counter-clockwise arc.
	G02/G03 <code>[X<math>n</math>] [Y<math>n</math>] [Z<math>n</math>] [I<math>n</math>] [J<math>n</math>] [K<math>n</math>] [F<math>n</math>] or</code> G02/G03 <code>[X<math>n</math>] [Y<math>n</math>] [Z<math>n</math>] [R<math>n</math>] [F<math>n</math>]</code>
	Circular interpolation. If an arc is specified using R rather than I/J/K, then a positive R-value produces an arc that subtends less than 180°; using a negative R-value produces an arc that's more than 180°. Also, various machines may treat the ZX plane slightly differently, depending on whether they are “standard” or “vertical machining.” So, G02 and G03 may be treated in opposite fashion. Basically, what does “clockwise” mean? See Smid, <i>CNC Programming Handbook</i> , p. 280. To cut a complete circle, the X/Y/Z values given with the command must be equal to the starting point of the tool, and you must use the I/J/K format, not an R-value. Geometrically, the distance of the center to each of the two end-points must be the same (that distance is the radius). When using the I/J/K format, it's not unusual for the center of an arc to require many digits to specify exactly, perhaps even an infinite number. So that the programmer only needs to input a reasonable number of digits, a certain amount of leeway must be allowed. Ger will accept a center if the distances to the two end-points are within 1% of each other, and it will assume that the radius of the circle is equal to the larger of these two distances.
G15	Polar coordinates off.
G16	Polar coordinates on. You may enter polar coordinate mode while in incremental mode (G91) or you may enter incremental mode after invoking G16, or go back to absolute mode (G90). Not every real-world CNC controller allows this. Ger also allows circular interpolation (G02/G03) while in polar coordinate mode, another thing that most real-world machines do not permit. Use of G01 or G00 while in polar coordinate mode is <i>not</i> allowed.
G17	Work in the XY-plane (the default).
G18	Work in the ZX-plane.

- G19 Work in the YZ-plane.  
While in cutter comp mode, only the standard XY-plane may be used. This is typical for real-world controllers.
- G20 Inches.
- G21 Millimeters.  
Ger works internally using either inches or millimeters, but you can freely change from one unit of measure to the other within your G-code. In fact, Ger is more flexible than many real-world controllers; you can sprinkle G20's and G21's all over the place. The only (?) reason the internal setting for GER matters is how it interprets things like tool tables.
- G28 Machine Zero Return. This is accepted, but everything from G28 to the end of the line (or a semi-colon) is ignored. On the simulated machine, it has the effect of moving the tool to the position of the tool turret.<sup>1</sup>
- G40 Cancel cutter comp, also known as "tool radius compensation."
- G41 Cutter comp, left.
- G42 Cutter comp, right.  
G41/G42 *Dw or*  
G41/G42 *Hw*  
The cutter comp is given relative to a value stored in a D-register or an H-register. The D-register typically contains the diameter of the tool and the H-register contains a value for tool wear. These are provided by using the "Tool Turret" dialog. As a reminder, the left/right distinction here refers to the position of the tool relative to its path. Thus, G41 puts the tool to the left of the path it follows.  
Ger does things slightly differently than how many real-world controllers seem to work. As soon as a G41/42 appears, the virtual machine peeks ahead to see what the next statement will be and it bumps the tool out by the tool radius to be ready to cut the very first curve with the correct cutter comp. I think this is better than the way it's typically done, but it could confuse people who are trying to test against a particular real-world machine. There seems to be so much variation from one controller to another in how this aspect of cutter comp is handled, that some degree of mis-match between Ger and the real world is unavoidable. In any case, the usual advice applies to *all* machines: invoke cutter comp away from the part and make at least one move before contacting the part.  
Note that Ger does not allow things like  
G41 X## Y## Z## D##

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<sup>1</sup>In fact, I'm not sure whether I've implemented this.

You can't have any extra stuff between the G41 and the D or H-register specification. Many real-world CNC machines do allow this.

One last point about cutter comp. Ger allows cutter comp to be used on interior angles, while many real-world controllers do not. However, Ger is not as smart as some real-world controllers about how it deals with this case. For instance, if the tool path is specified to form a very acute vertex, say  $5^\circ$ , and the tool makes many small moves (less than the tool radius) near this vertex, then the tool path in cutter comp mode might not be what you expect. On the other hand, it's hard to imagine what a person might intend in a case like this, so it seems better to let the tool do oddball things as a way of informing him that he *input* something oddball.

About the only situation I can imagine where this would arise is if you feed Ger code that was posted by a (rather stupid) CAM program. The way to "fix" this is to have infinite look-ahead in cutter comp mode so that Ger can remove all of those small moves near the apex from the statement stream, but it's not clear to me that this is something that *should* be fixed. It seems better for the controller to behave in a way that makes it apparent that the input G-code is weird, and probably wrong, rather than acting in a way that hides from the user potential problems with his G-code.

G43 Positive tool length offset (TLO).

G44 Negative tool length offset.

G49 Cancel tool length offset.

G43/G44 [Zn] Hw

The simulator considers the Z-value to be optional, although it is required by many real-world machines.

As a reminder, in the case of G43, this has the effect of adding the value in the H-register to all Z-moves until a G49 is reached. If the H-value is negative, then the tool will cut more deeply. G44 has the opposite effect.

A program may not enter TLO while in incremental mode, when using polar coordinates, or while in cutter comp mode. However, once TLO is in effect, a program may enter any of these modes. If your program does enter one of these modes, then it must leave these modes before cancelling TLO.

G52 Local coordinate system.

G52 [Xn] [Yn] [Zn]

This changes the origin to be the point at the given X, Y, Z, stated relative to the PRZ. All moves after G52 are as though the PRZ is at this new position. Each of the X, Y, and Z values is optional; omitted values are assumed to be zero (no change). This is cancelled with G54.

G54 Return to normal work offset. That is, use the PRZ as the origin. If a tool length offset is in force (G43 or G44), then it remains in force after calling G54.

G55

G56

G57

G58

G59 Codes G54 through G59 are similar to G52, but the values used for X, Y and Z come from the “work offsets” table. So, these codes appear alone, simply as G55 (say), without any additional codes. Just as with TLO mode, none of these codes, including G52, may be entered or exited while in incremental mode, polar coordinate mode, or cutter comp mode.

Normally, the values used for work offsets are the distance from machine zero to program zero (the PRZ), but the virtual machine has no “machine zero.” For the purpose of work offset settings, think of the PRZ as the machine zero. Put another way, the work offset values should be the amount in each direction, X, Y and Z, that you want the tool to be offset from the position it would have without the change due to applying one of G55 through G59.

G90 Absolute mode.

G91 Incremental mode.

As you can see, none of the canned cycles, like G81 for drilling, have been implemented. Some of them might manage to get through my system without causing an error, but none of them do anything. I haven’t thought very hard about this, but I don’t think that they would be hard to add.

Here are the valid M-codes.

M00

M01

M02 These are different forms of “program stop.” The simulator simply halts when it reaches one of these.

M03 Spindle on, clockwise.

M03  $Sw$   
where  $w$  is the spindle speed.

M04 Spindle on, counter-clockwise. Similar to M03. The program notes internally that the spindle is on, but it has no real effect.

M05 Spindle off.

M06 Tool change.

M06  $Tw$

changes to the tool in the  $w$  position of the turret. The simulator moves the tool in a straight line from its current position to the tool turret, changes to the new tool, and stops at that position.<sup>2</sup>

M07	
M08	
M09	These coolant on/off commands are accepted, but they do nothing.
M30	Halts the program.
M40	
M41	Spindle high/low. Accepted, but ignored.
M47	Repeat program. The simulator halts immediately if it reaches this code.
M48	
M49	Feed & speed override on/off. Accepted, but ignored.
M98	Call subprogram.
	M98 P $w$ L $w$
	This calls a sub-program, where P gives its number, and L gives the number of times to call it.
M99	Return from subprogram.

Two other codes are accepted: the O code for a program number, and N may be used for line numbers. Any line numbers given with N are ignored. Every program is required to start with an O-value.

If there are any errors in the program, then the line number on which the errors are detected are given by counting lines in the input text file, not with reference to any N-specified line numbers in the input G-code. Thus, if an error is reported on line 3 (say), then the problem was detected on the third line from the top, not the line that starts with N3 (assuming there is such a line).

Finally, comments are expressed with parenthesis, (...), as usual. The simulator accepts multi-line comments, but does not accept nested comments.

## 4 Transpiling

Ger works by transpiling (really, simplifying) the input code to the simplest possible subset of valid G-codes. This is done through a series of layers. When errors occur, it may be helpful to understand how the process of code simplification happens.

The first step is the lexical analyzer, or “lexer”. The lexer converts the input text to a sequence of “tokens.” These tokens are of one of a few types.

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<sup>2</sup>These motions don’t appear in the translator part of the program; they are used to detect tool crashes.

Ordinary G-code appears as a combination of letters, optionally followed by numbers. Examples include G0, M30, X3.205 and the like. The second type of token is associated with externally defined wizards. These include the function name, like `MyFunction`, and any arguments to such functions. These arguments are limited to numbers and strings delimited by a pair of double-quote ( " ) characters. The arguments to a wizard are space-delimited, and it is assumed that the arguments run to the end of the line on which the wizard is called.

The next layer is the parser. It converts the output from the lexer to syntactically valid statements.

## 5 Coordinate System

The coordinate system is inherently tied up with the particular physical machine on which the G-code is intended to run.<sup>3</sup> Each time a program starts, the tool is assumed to be located at  $(X,Y,Z) = (0,0,0)$ , and the machine defaults to working in inches. It's often unnecessary to consider the coordinate system in any further detail, but there are certain additional settings and controls available.

These codes are particularly related to the coordinate system:

```
G20/21 (inches/mm)
G28 (machine zero return)
G52/54 (local coordinate system/cancel)
G55/56/57/58/59 (use work offsets table)
G92 (I MIGHT WANT TO ADD THIS ONE).
```

### 5.1 Machine Zero and Work Offsets

The location of “machine home” or “machine zero” is the position of the tool at the start of the program; G28 always returns the tool to this position, in rapid mode. The PRZ (“program reference zero,” or “part reference zero”) starts off the same as machine zero, but can be adjusted with G52 or G55-G59. Absolute coordinates are always given relative to the current PRZ.

G52 is given with values for X, Y and Z, and each of these values defaults to zero if it is omitted. The location of the PRZ moves to the given (X,Y,Z) value relative to machine zero (which is fixed for all time). For example, after

```
G52 X1.000 Y2.000 Z0.500
```

appears, the location of (0,0,0) will be the same as (1,2,0.5) had been prior to the G52. Put another way, subtract the values given to G52 from all coordinates, and you have the location relative to machine zero.

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<sup>3</sup>In principle, it would be possible to specify the machine geometry sufficiently, including any tool turret, so as to detect tool crashes. But there are too many possible machine arrangements, and for this to work well, it would also be necessary to specify any jigs and fixtures.



The codes G55 through G59 works just as G52, except that the X, Y and Z values are taken from the “work offsets table.” This table is shared between all programs, and it is also possible to modify this table with the **SetWorkOffset** command before the O-command with the program number.

The PRZ is reset to machine zero with G54.

Blah, blah. Should probably just include most of the discussion in the long able above, with a few remarks here.

NOTE: It is tempting to simply get rid of the workoffset table and the commands related to it (G55, etc.). I don’t think people really use this.

The bottom line is that whenever a program starts, it assumed that the tool starts off at (0,0,0). This is the location to which G28 returns. You can also use G52/5/6/7/8/9 to change this and all of these are canceled by G54.

For the work offset tables, want there to be a table that could be used for every program, but it also makes sense to provide some special commands that can be used before the program starts to set these table values.

It also means that – if I want to specify the billet at all – then it needs to be done relative to the initial origin. The three ranges would be given in something like  $X = [a, b]$ ,  $Y = [c, d]$  and  $Z = [e, f]$ , where these values could be negative.

Exactly how to define the geometry of the machine and the part, together with various concepts of “origin,” is a difficult question. On the other hand, it’s often the case that certain obvious defaults will suffice. To fully define the geometry of the machine, follow these steps:

1. Define the size of the tool table.
2. Set the location of the tool turret relative to the lower-left corner of the tool table. The turret location is the position to which the spindle will return for a tool change.
3. Define the dimensions of the billet of material. By default, it is assumed to be centered on the tool table.
4. Set the PRZ relative to the billet. By default, this is taken to be at the lower-left corner of the billet.

The series of steps above is fussy and not necessary in most cases. Usually, it suffices to work with default settings. In this case, the billet is taken to be just large enough for the cuts that appear in the G-code (should allow setting some kind of margin) and the PRZ ends up being at the lower-left of the material. Tool changes happen in-place, without a move to a particular location for the tool turret. Things like work tables might be trickier though.

THIS WON’T WORK. For one thing, the tool table moves on some machines. Other machines might have the tool table move in only X or Y. It’s just too fiddly. What I need to do is break the list of codes up into the obvious ones, and the ones that are somehow sensitive to the machine geometry. The

commands that are somehow sensitive to the geometry are G28 (machine zero return), G43, G44, G49 (to do with tool length offset), G52-G59 (work offsets), M06 (tool change)

For things that have to do with the coordinate system, it's reasonable to make everything relative to a single PRZ, which can default to the lower-left corner of the billet, perhaps with some margin.

I will ignore the location of the tool changer, and just have the tool magically change in place. The user could redefine M06 somehow though to have it move to a certain location.

That leaves the tool length offset commands, and those aren't a big deal.

Overall, the best approach seems to be to specify all of this stuff within the G-code file. Each program could have different settings, and it's misleading to use the main window to do this. What could be done in the main window, as a kind of machine-wide setting, is the tool table. In any case, this is a more complicated thing that could be difficult to do with simple text.

So, what's needed is the following.

The first thing is to set the internal units used by the simulated machine. Say

```
SetUnits ["inch"|"mm"]
```

The default is "inch". This indicates the units for things like part dimensions and work offsets.

Once the units have been set, there are two ways to determine the part dimensions and machine zero (PRZ). The simplest is to say

```
SetMargin <value>
```

where <value> is the marginal amount that appears beyond the extent of where the tool cuts. In this case, the tool is assumed to touch the billet when the z-position drops below zero.

Another way to set the part dimension is to first say

```
SetPart <x> <y> <z>
```

where the values are the size of the raw (cubic) billet in the three dimensions. By default, machine zero (PRZ) is the top-lower-left of this material. The PRZ can be changed by saying

```
SetZero <x> <y> <z>
```

where the values are relative to the top-lower-left corner. For example,

```
SetPart 4.0 2.0 1.0
```

means that the part is  $4 \times 2 \times 1$  ( $x$  by  $y$  by  $z$ ). Now

```
SetZero 0.25 0.25 0.10
```

means that the PRZ is 0.25 in from the lower-left corner in both directions, and lowering the tool to  $Z=0$  cuts off the top 0.10 of the billet.

## Part I

# Old Java Version

## 6 System Overview

When the program is launched a window comes up with several menu choices. The “File” menu acts as you would expect. You can have multiple G-code programs open at the same time; each one appears in its own tab. You can edit and save programs from here too, although the editor is nothing fancy.

The “Render” menu generates a picture of the object described by the G-code program. There are two choices: “2D Display” and “3D Display”. Either choice generates a picture for the G-code in the foremost tab. The picture will appear in a new window, and the image is not automatically updated when you change the G-code. If you modify the G-code, and you want to see the result, choose “Render” again. Images for both versions of the G-code (new and old) will remain open. These images (and the data used to generate them) take a lot of memory. If you have several of these image windows open, then you could easily run out of memory.

Choosing “2D Display” shows a static image of the object, looking from above with each point shaded by the depth of cut. There is no user interaction (although you can make the window larger or smaller). If you choose “3D Display”, then you get an interactive 3D image of the object. You can’t use the mouse to rotate the image. Instead, use J and L to rotate left and right, I and M to rotate up and down, and U and O to twist the object in place. Use A and Z to zoom in and out. Also, X will close the window. Upper and lower case letters both work.

The “Settings” menu has several choices. Most of the choices should be self-explanatory, but not everything works. Both “Scale” and “Inches/mm” do work. If memory is tight, or if the image updates uncomfortably slowly, then reducing the scale should help. If the scale is  $s$ , then the virtual machine should work exactly as though the tool moves in steps of  $1/s$  inches (or millimeters). Put another way, it’s as though you multiplied all of the coordinates in your program by a constant. For instance, if you change the scale from 1,000 to 100, that’s like multiplying all coordinates by 0.10. For objects that are only a few inches in size and are of modest complexity, leaving the scale at 1000.0 should be fine, but for large objects, you may need to make this smaller. In fact, unless you’re doing something really intricate, a value of 100 (or even less) is probably fine.

The “Work Offsets” dialog does work (although it hasn’t been very thoroughly tested), and it should be clear what to do.

Don't try to use the "Uncut Shape" dialog. It's meant as a way for the user to indicate the size of the raw material, but it doesn't work. Right now, the program will automatically use an object that's large enough to encompass all cuts made by the program.

The "Tool Table" works, but only up to a point. The system recognizes  $D$  and  $H$  values from this table when using cutter comp and tool length offsets, and it knows the diameter of the tool. What it can't do is use anything other than simple endmills. If you change the diameter value in the  $D$ -column, then you must hit the return/enter key to tell dialog that you mean it before you click the "OK" button. One last thing: there's a secret default tool. This tool has a cutting diameter of 0.020 inches, but the cutter comp is 0.250 inches. This is handy sometimes when you're trying to understand what cutter comp is doing; it makes it easier to visualize the actual path of the tool. If there's no M06 in your program, then you'll get the secret default tool.

Concerning Java and memory...When you launch the program that I wrote, your computer isn't really running my program. The computer runs Java, which in turn opens up and runs my program. This means that, whenever my program needs more memory, it must ask the Java system for the memory it needs. You may have oodles of memory on your machine, but Java won't let my program use it unless you tell Java that it's OK. I provided one way around this problem (a .bat file), but there are others.

## 7 G-codes and M-codes

I tried to implement all of the G-codes that one might care about and that are likely to be consistent across different makes of controller. Here's a list, with some comments.

- G00 Rapid travel.
- G01 Ordinary move. There are no surprises with these two. However, for all practical purposes, my program makes no distinction between G00 and G01. The program does not check for things like whether the spindle is on when you cut, or whether you're trying to cut in rapid mode. Likewise, the program accepts a feed rate (F-value), but the feed rate has no effect on the output.
- G02
- G03 Circular interpolation. These do what you'd expect, although I'm not very confident that they work correctly if you are not in G17 mode.
- G04 Dwell. This is accepted, but ignored. Actually, it might cause an error, depending on how you use it. I'm not sure.
- G15 Polar coordinates off.
- G16 Polar coordinates on. Again, using G18 and G19 might not work right. I tried to make them work correctly, but it hasn't been thoroughly tested.

- G17
- G18
- G19 See above and below for caveats about G18 and G19.
- G20 Inches.
- G21 Millimeters. The abstract machine works internally in either inches or millimeters, but you can freely change from one unit of measure to the other within your G-code. In fact, my program is probably more flexible than many real controllers, perhaps dangerously so. You can sprinkle G20's and G21's all over the place.
- G28 This is accepted, but ignored. Smid calls it "machine zero return"; I'm not sure exactly what it should do.
- G40 Cancel cutter comp.
- G41 Cutter comp, left.
- G42 Cutter comp, right. These work as they should, but (as usual) they might be wrong under G18 and G19. Also, I do things differently than how most real CNC machines seem to work. As soon as a G41/42 appears, the virtual machine peeks ahead to see what the next statement will be, and it bumps the tool out by the cutter comp amount to be ready to cut the very first curve with the correct cutter comp. I think this is better than the way it's typically done, but it could confuse people who are trying to test against a particular real-world machine. Anyway, there seems to be so much variation from one machine to another in how this aspect of cutter comp is handled, that some degree of mismatch between my virtual machine and the real world is unavoidable.
- Dealing with cutter comp is messy and it's the thing most likely to have bugs. Also I chose to handle cutter comp by using what are probably very unorthodox methods. They are powerful, in the sense that I could extend my program to handle cutter comp on (as yet unspecified) curves that are more complex than line segments and arcs of circles, but there could be bugs for reasons that are hard to track down.
- G43 Tool length offset, in the normal case.
- G44 Tool length offset, in the negative sense. I doubt that this is used often, but it works.
- G49 Cancel tool length offset. Tool length offset works as it should. One oddity is due to the fact that, in a virtual machine, tools don't have a natural length. For the time being, treat all tools as though the machine magically knows where the tip of every tool is. If you use G43 after setting  $H = 0$  in the tool table, then it will act like it should. If  $H > 0$ , then the tool will cut more deeply under G43 and less deeply under G44.
- G52 Allows you to specify a new local reference frame. This is something like a work offset (G54,...,G59), but the coordinates are specified in the program, and must be given relative to the PRZ.

G54  
 G55  
 G56  
 G57  
 G58  
 G59 To change work offsets. These work as you would expect, but the coordinates must be given relative to the PRZ in the work offset table. There's no natural way to define "machine coordinates" other than the PRZ.  
 G90 Absolute mode.  
 G91 Incremental mode. These work as expected.

As you can see, none of the canned cycles, like G81 for drilling, have been implemented. Some of them might manage to get through my system without causing an error, but none of them do anything. I haven't thought very hard about this, but I don't think that they would be hard to add.

Here are the valid M-codes.

M01 Smid calls this "compulsory program stop."  
 M02 And he calls this "optional program stop." In both cases, I make the program halt, like an M30.  
 M03 Spindle on, clockwise.  
 M04 Spindle on, counter-clockwise. The program notes internally that the spindle is on, but it has no real effect.  
 M05 Spindle off.  
 M06 Tool change.  
 M07  
 M08  
 M09 These coolant on/off commands are accepted, but they do nothing.  
 M30 Halts the program.  
 M40  
 M41 Spindle high/low. Accepted, but ignored.  
 M47 Repeat program. Since I'm not sure exactly what this should do, it generates an error.  
 M48  
 M49 Feed & speed override on/off. Accepted, but ignored.  
 M98 Call subprogram.  
 M99 Return from subprogram. Both of these work.

The system also accepts line numbers (with N), but they don't have any meaning since none of the valid codes can refer to line numbers.

## 8 Shortcomings

The most obvious shortcoming is that it can be slow to bring up the image. Once the image is up, it's reasonably fast to move around in 3D. The larger the tool is, the slower it is. If the tool is only 0.020 in diameter, then it's plenty fast, but a tool that's 0.250 in diameter takes roughly 150 times as long as a tool that's only 0.020 in diameter. Having to wait 10 seconds, or even a minute for the image to come up is possible. In round numbers, with a quarter inch endmill, you can expect to wait 0.25 seconds for every inch of tool travel (at least that's true on my machine). I have ideas about how to fix this, but it will take some time to make the necessary changes. As a quick fix, you can change the scale value from 1,000 to something like 100.

The other big problem is the fact that the program is a memory hog. There are things I can do to improve matters, but some amount of hoggishness is unavoidable. The program isn't very nice about its memory needs; it may crash if it can't get the memory it wants.

You'll notice that, in 3D mode, the image you get isn't really a solid object at all; it's just the "skin" of the object's top. Making the object appear as a solid is easy, but I find that, given the less than ideal method of shading that I use now, it's easier to visualize what's been cut if the object isn't solid.

Objects that are large and/or intricate will be drawn slowly in 3D mode. You'll notice this for anything larger than about three inches square. I mentioned above that you can reduce the scale value as a crude fix for this problem. Doing that makes the internal representation of the object less detailed. I have ideas about how I can improve the speed, but implementing these idea will take some time.

The way the object is shaded isn't the greatest. Right now, the surface of the object is shaded based on the depth of the cut. This is OK most of the time, but sometimes it would be nice if there were more contrast between adjacent surfaces. I know how to fix this (I think), but it's non-trivial.

If you zoom in too far on objects, the program may crash. I know exactly why this happens, but I'm probably going to totally redo that part of the program anyway, so I don't want to deal with the problem.

Even for very simple objects, there's an internal limit on the permitted size of the object. This limit is roughly a cube 32 inches on each side. I could allow objects that are literally miles to the side by doubling the memory requirements, but, unfortunately, there's no middle ground. In any case, my current less efficient methods of memory usage dictate a limit of roughly a square six inches on a side.

## 9 Bonus

The "Test" menu is there for my own debugging purposes. It's not meant to be very clean, but there are a few things there that you might think are interesting.

The output of "Test Voxel Frame" looks something like what you see in the

3D window under Mach3. Every tool position gets a dot in three-dimensional space, and this draws those dots. The drawing is cruddy, but it wasn't really meant for public consumption. You can rotate and zoom using the keyboard.

Choosing "Test Pulses" will show the series of pulses (zeros and ones) generated by the G-code. These are the signals that would be sent to the motors of a real-world CNC machine. Again, this was for debugging, and I think that it only shows the first 100 pulses.

The other choices under the "Test" menu have to do with the way that my program converts G-code to pulses. It's a multi-step process that begins with the lexer (in computer science lingo, the "lexical analyzer"). The lexer converts the string of characters that make up the G-code into bite-sized pieces that later stages find easier to digest. For instance, the lexer converts

```
X0.100 Y1.500
```

into two "tokens", one for the X-value and another for the Y-value. That's probably not so interesting to you, but the other layers of the process might be.

The parser takes the tokens from the lexer and converts them to meaningful statements. Basically it verifies that the G-code isn't absolute gibberish. The output of "Parsify" should look pretty much like the input G-code.

The next five steps, "Simplify 00" through "Simplify 05" take the original G-code and convert it to G-code of a simpler and simpler form. The 00 step eliminates subroutine calls. The output is exactly what you would have to type (over and over again) if there were no such thing as M98/99. The 01 step converts everything to the standard unit of the machine (inches or millimeters) so that G20/21 no longer appear in the G-code. The 02 step removes any work offsets so that G52 and G54 through G59 are eliminated, along with G43, 44, 49 for tool length offset. All coordinate values generated by step 01 are adjusted as needed. The 03 step gets rid of polar coordinates. The 04 step changes all coordinate values to be absolute so that G90/91 is not needed in the output, and step 05 adjusts everything for cutter comp.

The output of step 05 is exactly the G-code that you would have to type to create the same object as the original G-code, but on a machine that understands only G00, G01, G02 and G03, along with the M-codes for tool change and spindle & coolant control. The ability to see the output of this final step may be useful from a teaching point of view. It would help students to visualize what cutter comp and subroutine calls (for example) really do.

## Part II

# C++/Qt Version

## 10 What is This Thing?

For the time being, I am calling this program "Ger," which I got by combining "G," as in "G-code," with the "er" sound of "verify." So, the program is a



G-code verifier or a “Gerifier” – “Ger” for short. You can pronounce as in the name Gary (or Jerry) when you feel friendly toward the program, or a bear’s growl when the program isn’t doing what you want it to, which shouldn’t be very often.

I thought of calling the program “Gim,” as in “G-code simulator,” but I’ll bet that name is taken for something. If you think of a better name, let me know.

**As you use this program, please let me know if you find anything about it that doesn’t seem right. Obviously, if it translates your code in a way that doesn’t make sense, I want to know about that. In fact, I’d like to hear about anything odd or unexpected that the program does. If you see an inefficiency, inelegance, or just have a good idea related to the program, then I want to hear about that too. If you do find any bugs, it will help me if you can send me the input G-code and/or explain (in detail!) what you did that led to the strange behavior. I can’t fix a bug that I can’t reproduce. I am at rsfairman@yahoo.com.**

At this point the program can do two things: translating G-code to a simpler form and rendering a two-dimensional image of the part being cut.

## 10.1 Translation

You can give Ger some G-code, and have it spit out a simplified version of the code you gave it. Here’s what I mean.

Fundamentally, any G-code program boils down to having the tool do one of two things: move linearly or move along a circular arc – there are also helical moves, but these are just a combination of a linear move and an arc move. For example, if the program you input involves cutter compensation (G42), work offsets (G56), polar coordinates (G16), incremental mode (G91), and so forth, then the output program will have the same effect as the input program – will move the tool in the same way and cut the same part – but it won’t involve any of these more complicated commands. The output program will involve only G00, G01, G02 and G03.

In fact, there are a few codes in addition to these four that can’t be eliminated from the output program. These additional codes are G17/18/19, which specify which of the XY, ZX or YZ-plane to work in, along with the M-codes for spindle start/stop (M03/04/05) and tool change (M06). In a section below, there is a list of the G/M-codes that Ger accepts as input, along with a brief description of what each one does.

The translator is useful for several things. It’s a good teaching tool. The more esoteric G-codes can be difficult to understand, and once you do understand them, it’s easy to forget how they work. By running your G-code through Ger, and looking at the output, you can check your understanding of particular codes.

Second, not all controllers are very friendly about certain G-codes. For instance, I have had bad luck using cutter comp on Mach3. Maybe it’s me, but

I've had Mach3 go haywire too many times when I was using cutter comp to trust it. Using Ger, you can write your program with cutter comp, have Ger translate it to a program which does the same thing, but does it without cutter comp, and give that simpler program to the real-life controller.

Third, even experts get confused. If you're writing a long program, particularly one that uses sub-programs and incremental mode, it's easy to get mixed up about where the tool is at a particular point in the program. Ger expresses its output strictly in absolute mode, making it easy to check that the tool is where you think it is as the program proceeds. If the tool is not where you think it should be, then Ger makes it easy to find out where your program went wrong.

## 10.2 2D Rendering

Ger is able to show a flat (2D) image of the object cut by your G-code (I'm working on 3D rendering, but it's not ready yet). The depth of cut is indicated by the shade of gray used, with darker areas being cut more deeply.

Once the image is visible, you can drag it around with the mouse or zoom in and out by using the mouse wheel. Double-click on the image to bring it back to the standard view showing the entire object centered in the window. You can use the keyboard instead of the mouse: use the arrow keys to pan the image, the plus and minus keys to zoom in and out, and the enter key to return to the standard view.

## 11 Overview of Menus

When the program is launched a window comes up with several menu choices. The "File" and "Edit" menus act as you would expect. You can have multiple G-code programs open at the same time; each one appears in its own tab. You can edit and save programs from here too, although the editor is nothing fancy. You can adjust how much space each of the left and right panes has by dragging the divider between them.

Use the "Action" menu to perform a translation/simplification of your G-code or to show an image of the object. After you've loaded some G-code, either by opening a file or by typing it in, choose "Translate" and a simplified version of your program will appear in the right panel. The format is basically the same as ordinary G-code, although it's been restated to use only the most fundamental linear and arc moves. The line numbers that appear on the right (the N-values) refer to the line in the input file that lead to that line of output. You can use this to understand where your input program went wrong – why didn't the simulated controller move the tool in the way I thought my G-code specified?

The "Action" menu is where you can bring up a various dialog boxes that set up the simulated machine. The "Set Geometry" dialog allows you to define

the dimensions of the raw material being machined, whether to work in inches or millimeters, the location of the PRZ (*i.e.*, the origin) and the tool turret.

The “Tool Table” dialog allows you to specify up to 20 tools in the turret. Ger is able to cut with endmills, ballmills (cutters with a hemispherical tip), center drills and ordinary drills. In fact, a “drill” is treated as if it were an ordinary pointy-ended mill; you can make linear cuts or plunging cuts with one. Programs change tools in the ordinary way, by using M06. For instance, M06 T3 changes to the third tool in the turret. If a program doesn’t specify a particular tool, then it defaults to the first tool in the turret, which is a quarter-inch endmill.

If your program invokes G55/56/57/58/59, then use the “Work Offsets” dialog to set the corresponding values.

Finally, the “Scale” dialog allows you to adjust the level of detail at which the program works. For most uses, it’s not necessary for rendered images to be calculated to 0.001 in – at that level of detail a square inch of material would fill an unusually large computer monitor. If you do need more detail, the “Scale” dialog allows you to get it, although the rendering process may take up to 100 times longer and use 100 times the memory.

To show an image of the part cut by your G-code, choose “Render – 2D.” If you modify the G-code, and you want to see the result, choose “Render – 2D” again.

## 12 G-codes and M-codes

Different controllers use slightly different variations of the G/M-codes. Ger tries to take a middle-of-the-road approach, although it is more flexible than many real-world controllers about the order and grouping of codes. For instance, something like this is accepted:

```
G01 X1.0 G21 G01 Y250.0
```

and would be interpreted as

```
G01 X1.0  
G21  
G01 Y250.0
```

Statements may be terminated by either a new-line (*i.e.*, a “carriage return” or “enter”), or by a semi-colon. Thus, G01 X1.0; Y2.0 is valid and means something entirely different than G01 X1.0 Y2.0. If it is possible for *you* to make sense of your program by reading the codes one “chunk” at a time, then the simulator can probably make sense of it too, although the controller on the actual milling machine may be more strict.

Many of the codes that make sense on a real-world machine are ignored by the simulator. For instance, M08, M09 (coolant on/off) is ignored, and M47 (repeat program) doesn’t really make sense in this context.

To be clear on how this program interprets the different codes, here's a list of how they are seen by the program's virtual controller. The table below is organized by "actionable chunks," meaning a series of inputs that makes sense together. To make the descriptions more concise, [...] is used for an optional term, *n* means a number, possibly with a decimal, and *w* means a whole number.

<i>Move</i>	[ <i>Xn</i> ] [ <i>Yn</i> ] [ <i>Zn</i> ] [ <i>Fn</i> ]
	Notice the use of [ and ]: each of these terms is optional. This command moves the tool along a line segment to the given X, Y, Z, at the given feed rate. If you are in rapid mode (G00), then the F is not allowed.
G00	Rapid travel mode. The program begins in rapid travel mode. If the very first line is X1.000 Y1.000, then the tool will move to that position in rapid mode.
G01	Ordinary (not rapid) travel mode.
G02	Clockwise arc.
G03	Counter-clockwise arc.
	G02/G03 [ <i>Xn</i> ] [ <i>Yn</i> ] [ <i>Zn</i> ] [ <i>In</i> ] [ <i>Jn</i> ] [ <i>Kn</i> ] [ <i>Fn</i> ] or G02/G03 [ <i>Xn</i> ] [ <i>Yn</i> ] [ <i>Zn</i> ] [ <i>Rn</i> ] [ <i>Fn</i> ]
	Circular interpolation. These do what you'd expect. Something to remember: if an arc is specified using R rather than I/J/K, then a positive R-value produces an arc that subtends less than 180°; using a negative R-value produces an arc that's more than 180°. Also, various machines may treat the ZX plane slightly differently, depending on whether they are "standard" or "vertical machining." So, G02 and G03 may be treated in opposite fashion. Basically, what does "clockwise" mean? See Smid, <i>CNC Programming Handbook</i> , p. 280. To cut a complete circle, the X/Y/Z values given with the command must be equal to the starting point of the tool, and you must use the I/J/K format, not an R-value. Geometrically, the distance of the center to each of the two end-points must be the same (that distance is the radius). When using the I/J/K format, it's not unusual for the center of an arc to require many digits to specify exactly, perhaps even an infinite number. So that the programmer only needs to input a reasonable number of digits, a certain amount of leeway must be allowed. Ger will accept a center if the distances to the two end-points are within 1% of each other, and it will assume that the radius of the circle is equal to the larger of these two distances.
G04	Dwell. This is accepted, but everything from G04 to the end of the line (or a semi-colon) is ignored.
G15	Polar coordinates off.
G16	Polar coordinates on.

You may enter polar coordinate mode while in incremental mode (**G91**) or you may enter incremental mode after invoking **G16**, or go back to absolute mode (**G90**). Not every real-world CNC controller allows this. Ger also allows circular interpolation (**G02/G03**) while in polar coordinate mode, another thing that most real-world machines do not permit. Use of **G01** or **G00** while in polar coordinate mode is *not* allowed.

**G17** Work in the XY-plane (the default).

**G18** Work in the ZX-plane.

**G19** Work in the YZ-plane.

While in cutter comp mode, only the standard XY-plane may be used. This is typical for real-world controllers.

**G20** Inches.

**G21** Millimeters.

Ger works internally using either inches or millimeters, but you can freely change from one unit of measure to the other within your G-code. In fact, Ger is more flexible than many real-world controllers; you can sprinkle **G20**'s and **G21**'s all over the place.

**G28** Machine Zero Return. This is accepted, but everything from **G28** to the end of the line (or a semi-colon) is ignored. On the simulated machine, it has the effect of moving the tool to the position of the tool turret.<sup>4</sup>

**G40** Cancel cutter comp, also known as “tool radius compensation.”

**G41** Cutter comp, left.

**G42** Cutter comp, right.

**G41/G42** *Dw or*

**G41/G42** *Hw*

The cutter comp is given relative to a value stored in a D-register or an H-register. The D-register typically contains the diameter of the tool and the H-register contains a value for tool wear. These are provided by using the “Tool Turret” dialog. As a reminder, the left/right distinction here refers to the position of the tool relative to its path. Thus, **G41** puts the tool to the left of the path it follows.

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<sup>4</sup>In fact, I’m not sure whether I’ve implemented this.

Ger does things slightly differently than how many real-world controllers seem to work. As soon as a G41/42 appears, the virtual machine peeks ahead to see what the next statement will be and it bumps the tool out by the tool radius to be ready to cut the very first curve with the correct cutter comp. I think this is better than the way it's typically done, but it could confuse people who are trying to test against a particular real-world machine. There seems to be so much variation from one controller to another in how this aspect of cutter comp is handled, that some degree of mis-match between Ger and the real world is unavoidable. In any case, the usual advice applies to *all* machines: invoke cutter comp away from the part and make at least one move before contacting the part.

Note that Ger does not allow things like

G41 X## Y## Z## D##

You can't have any extra stuff between the G41 and the D or H-register specification. Many real-world CNC machines do allow this.

One last point about cutter comp. Ger allows cutter comp to be used on interior angles, while many real-world controllers do not. However, Ger is not as smart as some real-world controllers about how it deals with this case. For instance, if the tool path is specified to form a very acute vertex, say  $5^\circ$ , and the tool makes many small moves (less than the tool radius) near this vertex, then the tool path in cutter comp mode might not be what you expect. On the other hand, it's hard to imagine what a person might intend in a case like this, so it seems better to let the tool do oddball things as a way of informing him that he *input* something oddball.

About the only situation I can imagine where this would arise is if you feed Ger code that was posted by a (rather stupid) CAM program. The way to "fix" this is to have infinite look-ahead in cutter comp mode so that Ger can remove all of those small moves near the apex from the statement stream, but it's not clear to me that this is something that *should* be fixed. It seems better for the controller to behave in a way that makes it apparent that the input G-code is weird, and probably wrong, rather than acting in a way that hides from the user potential problems with his G-code.

G43 Positive tool length offset (TLO).

G44 Negative tool length offset.

G49 Cancel tool length offset.

G43/G44 [Zn] Hw

The simulator considers the Z-value to be optional, although it is required by many real-world machines.

As a reminder, in the case of G43, this has the effect of adding the value in the H-register to all Z-moves until a G49 is reached. If the H-value is negative, then the tool will cut more deeply. G44 has the opposite effect.

A program may not enter TLO while in incremental mode, when using polar coordinates, or while in cutter comp mode. However, once TLO is in effect, a program may enter any of these modes. If your program does enter one of these modes, then it must leave these modes before cancelling TLO.

G52 Local coordinate system.

G52 [X $n$ ] [Y $n$ ] [Z $n$ ]

This changes the origin to be the point at the given X, Y, Z, stated relative to the PRZ. All moves after G52 are as though the PRZ is at this new position. Each of the X, Y, and Z values is optional; omitted values are assumed to be zero (no change). This is cancelled with G54.

G54 Return to normal work offset. That is, use the PRZ as the origin. If a tool length offset is in force (G43 or G44), then it remains in force after calling G54.

G55

G56

G57

G58

G59 Codes G54 through G59 are similar to G52, but the values used for X, Y and Z come from the “work offsets” table. So, these codes appear alone, simply as G55 (say), without any additional codes. Just as with TLO mode, none of these codes, including G52, may be entered or exited while in incremental mode, polar coordinate mode, or cutter comp mode.

Normally, the values used for work offsets are the distance from machine zero to program zero (the PRZ), but the virtual machine has no “machine zero.” For the purpose of work offset settings, think of the PRZ as the machine zero. Put another way, the work offset values should be the amount in each direction, X, Y and Z, that you want the tool to be offset from the position it would have without the change due to applying one of G55 through G59.

G90 Absolute mode.

G91 Incremental mode.

As you can see, none of the canned cycles, like G81 for drilling, have been implemented. Some of them might manage to get through my system without causing an error, but none of them do anything. I haven’t thought very hard about this, but I don’t think that they would be hard to add.

Here are the valid M-codes.

M00  
M01  
M02 These are different forms of “program stop.” The simulator simply halts when it reaches one of these.  
M03 Spindle on, clockwise.  
M03 *Sw*  
where *w* is the spindle speed.  
M04 Spindle on, counter-clockwise. Similar to M03. The program notes internally that the spindle is on, but it has no real effect.  
M05 Spindle off.  
M06 Tool change.  
M06 *Tw*  
changes to the tool in the *w* position of the turret. The simulator moves the tool in a straight line from its current position to the tool turret, changes to the new tool, and stops at that position.<sup>5</sup>  
M07  
M08  
M09 These coolant on/off commands are accepted, but they do nothing.  
M30 Halts the program.  
M40  
M41 Spindle high/low. Accepted, but ignored.  
M47 Repeat program. The simulator halts immediately if it reaches this code.  
M48  
M49 Feed & speed override on/off. Accepted, but ignored.  
M98 Call subprogram.  
M98 *Pw Lw*  
This calls a sub-program, where *P* gives its number, and *L* gives the number of times to call it.  
M99 Return from subprogram.

Two other codes are accepted: the *O* code for a program number, and *N* may be used for line numbers. Any line numbers given with *N* are ignored. Every program is required to start with an *O*-value.

If there are any errors in the program, then the line number on which the errors are detected are given by counting lines in the input text file, not with reference to any *N*-specified line numbers in the input G-code. Thus, if an error is reported on line 3 (say), then the problem was detected on the third line from the top, not the line that starts with *N3* (assuming there is such a line).

Finally, comments are expressed with parenthesis, *(...)*, as usual. The simulator accepts multi-line comments, but does not accept nested comments.

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<sup>5</sup>These motions don’t appear in the translator part of the program; they are used to detect tool crashes.