the Halting Collection

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Halting Problem

When Alan Turing laid the foundation for computation in 1936, he wanted to show what computation can do, and what it cannot do. For the latter, he invented a problem that we now call the “Halting Problem”. In modern terms, it is as follows.

In a general-purpose programming language, write a program that reads a text (character string) \( p \) representing a program, and reads another text \( i \) representing its input, and outputs true if execution of \( p \) with input \( i \) terminates, and outputs false if execution of \( p \) with input \( i \) does not terminate.

The problem cannot be solved; there is no such program.

This paper is a collection of ten interestingly different versions of the Halting Problem that I have encountered or invented. I present the proofs without mingling any criticisms or comments in them; for criticisms and comments, see http://www.cs.utoronto.ca/~hehner/halting.html. I leave you to decide their validity for yourself.

Turing's Argument

Here is the key paragraph from Turing's paper. To help the modern reader, I have added the square bracketed words.

Let us suppose that there is a such a process; that is to say, that we can invent a machine D which, when supplied with the S.D [standard description] of any computing machine M will test this S.D and if M is circular [nonterminating] will mark the S.D with the symbol "u" [unsatisfactory] and if it is circle-free [terminating] will mark it with "s" [satisfactory]. By combining the machines D and U [universal machine, or interpreter] we could construct a machine H to compute the sequence beta' [a sequence that differs from the diagonal with U]. ... Now let K be the D.N [description number, or code] of H. What does H do in the Kth section of its motion? [What happens when H works on the representation of H?] It must test whether K is satisfactory, giving a verdict "s" or "u". Since K is the D.N of H and since H is circle-free, the verdict cannot be "u". On the other hand, the verdict cannot be "s".

For if it were, then in the Kth section of its motion H would be bound to compute the first R(K-1)+1 = R(K) figures [R(n) is the number of terminating programs among the first n programs] of the sequence computed by the machine with K as its D.N and to write down the R(K)th as a figure of the sequence computed by H. The computation of the first R(K)-1 figures would be carried out all right, but the instructions for calculating the R(K)th would amount to "calculate the first R(K) figures computed by H and write down the R(K)th". This R(K)th figure would never be found. I.e., H is circular, contrary both to what we have found in the last paragraph and to the verdict "s". Thus both verdicts are impossible and we conclude that there can be no machine D.
Pascal Version

I cannot write a Pascal function to say whether the execution of any Pascal procedure halts, so instead I write the function header, and a comment to specify what the result of the function is supposed to be. Following that is a procedure to which the function can be applied.

```pascal
function halts (p, i: string): boolean;
{ returns true if string p represents a Pascal procedure with one string input }
{ whose execution halts when given input i; returns false otherwise }

procedure diag (s: string);
begin
  if halts (s, s) then diag (s)
end
```

We assume there is a dictionary of function and procedure definitions that is accessible to `halts`, so that the call `halts ('diag', 'diag')` allows `halts` to look up `diag`, and subsequently `halts`, in the dictionary, and retrieve their texts for analysis.

Assume function `halts` has been programmed according to its specification. Does execution of `diag ('diag')` terminate? If it terminates, then `halts ('diag', 'diag')` returns `true` according to its specification, and so we see from the body of `diag` that execution of `diag ('diag')` does not terminate. If it does not terminate, then `halts ('diag', 'diag')` returns `false`, and so execution of `diag ('diag')` terminates. This is a contradiction (inconsistency). Therefore function `halts` cannot have been programmed according to its specification.
No Input Version

This version is a simplification of the previous version. The input parameter is unnecessary to the proof, so it has been eliminated.

```pascal
function halts (p: string): boolean;
{ returns true if string p represents a parameterless Pascal procedure }
{ whose execution halts; returns false otherwise }

procedure diag;
begin
    if halts ('diag') then diag
end
```

We assume there is a dictionary of function and procedure definitions that is accessible to halts, so that the call halts ('diag) allows halts to look up 'diag', and subsequently 'halts', in the dictionary, and retrieve their texts for analysis.

Assume function halts has been programmed according to its specification. Does execution of diag terminate? If it terminates, then halts ('diag') returns true according to its specification, and so we see from the body of diag that execution of diag does not terminate. If it does not terminate, then halts ('diag') returns false, and so execution of diag terminates. This is a contradiction (inconsistency). Therefore function halts cannot have been programmed according to its specification.

Specialized Version

This version is a further simplification. Although halts was defined to apply to any procedure, the proof applies it to only one procedure. So we can write a specialized version of halts that applies to only that one procedure, and the proof remains intact.

```pascal
function halts: boolean;
{ returns true if execution of diag terminates; returns false otherwise }

procedure diag;
begin
    if halts then diag
end
```

Assume function halts has been programmed according to its specification. Does execution of diag terminate? If it terminates, then halts returns true according to its specification, and so we see from the body of diag that execution of diag does not terminate. If it does not terminate, then halts returns false, and so execution of diag terminates. This is a contradiction (inconsistency). Therefore function halts cannot have been programmed according to its specification.

Since halts has no parameters, it is a constant function. Its body must be either halts := true or halts := false (that's Pascal for return true and return false).
Formal Proof Version

This version is just like the “No Input Version”, but instead of using Pascal, it uses a notation that is more amenable to formal proof. Define

\[ \text{halts} = (\text{a function that maps texts representing parts of programs to their halting status}) \]
\[ \text{loop} = (\text{a statement or procedure whose execution does not terminate}) \]
\[ \text{stop} = (\text{a statement or procedure whose execution terminates}) \]
\[ \text{diag} = “\text{if halts (diag) then loop else stop}” \]

Now calculate.

\[ \text{halts (diag)} \]
\[ = \text{halts (” if halts (diag) then loop else stop ”)} \] \hspace{1cm} \text{definition of diag}
\[ = \text{if halts (diag) then halts (”loop”) else halts (”stop”)} \] \hspace{1cm} \text{semantic transparency}
\[ = \text{if halts (diag) then false else true} \] \hspace{1cm} \text{definitions of halts, loop, and stop}
\[ = \neg \text{halts (diag)} \] \hspace{1cm} \text{boolean algebra}

The inconsistency we arrive at does not depend on whether \text{halts} is a programmed function or mathematical function. The semantic transparency step implicitly assumes that if \text{halts} is a programmed function, then execution of \text{halts (diag)} is terminating. That assumption could be made explicit by adding the axiom

\[ \text{halts (“halts (” s “”)”)} \]

where \( s \) is a text representing a part of a program, and text catenation is represented by juxtaposition. Then the calculation is as follows.

\[ \text{halts (diag)} \]
\[ = \text{halts (“ if halts (diag) then loop else stop ”)} \] \hspace{1cm} \text{definition of diag}
\[ = \text{halts (“halts (diag)”)} \land \text{if halts (diag) then halts (”loop”) else halts (”stop”)} \] \hspace{1cm} \text{apply \text{halts} to “if...”}
\[ = \text{true} \land \text{if halts (diag) then false else true} \] \hspace{1cm} \text{use the \text{halts} axiom and the definitions of halts, loop, and stop}
\[ = \neg \text{halts (diag)} \] \hspace{1cm} \text{boolean algebra}
Direct Version

A proof-by-contradiction makes the assumption that halting is computable, then finds an inconsistency, and concludes that the assumption was wrong. This version does not begin that way.

Choose a programming language that includes the text (character string) data type and the boolean data type. Define

\[
\begin{align*}
  h &= \text{(the mathematical function that maps texts representing programs to their halting status)} \\
  T &= \text{(a program whose execution terminates)} \\
  N &= \text{(a program whose execution does not terminate)} \\
  P &= \text{(a program that applies to texts with boolean result)} \\
  D &= \text{“if } P(D) \text{ then } N \text{ else } T \text{”}
\end{align*}
\]

Now calculate

\[
\begin{align*}
  \text{true} & \quad \text{definition of } D \\
  \implies h(D) &= h(\text{“if } P(D) \text{ then } N \text{ else } T \text{”}) \quad \text{function transparency} \\
  \equiv h(D) &= (h(\text{“}P(D)\text{”}) \land \text{if } P(D) \text{ then } \text{“}N\text{”} \text{ else } \text{“}T\text{”}) \quad \text{interpretation} \\
  \equiv h(D) &= (h(\text{“}P(D)\text{”}) \land \text{if } P(D) \text{ then } \bot \text{ else } T) \quad \text{definitions of } N \text{ and } T \\
  \equiv h(D) &= (h(\text{“}P(D)\text{”}) \land \neg P(D)) \quad \text{boolean algebra}
\end{align*}
\]

For program \( P \) to be an implementation of function \( h \), \( P \) has to apply to at least the domain of \( h \) (it does), and on the domain of \( h \) it has to give the same results as \( h \). Suppose \( h(D) \) is \textit{true} . Then in the last line of the calculation, \( h(\text{“}P(D)\text{”}) \land \neg P(D) \) means that execution of \( P(D) \) terminates with result \textit{false} , and so \( P \) is not an implementation of \( h \). Suppose \( h(D) \) is \textit{false} . Then, according to the last line of the calculation, either execution of \( P(D) \) does not terminate, or \( P(D) \) is \textit{true} , and so again \( P \) is not an implementation of \( h \). In all cases, \( P \) is not an implementation of \( h \). Since \( P \) was any program from texts to booleans, the halting function is incomputable.
Self-Duplicating Version

The trick used in this version is due to W.V.O. Quine.

Define

\[ q = \text{(the opening quotation mark)} \]
\[ Q = \text{(the closing quotation mark)} \]
\[ D(x, y, z) = x q x Q y q y Q y q z Q z \]
\[ T = \text{(a program whose execution terminates)} \]
\[ N = \text{(a program whose execution does not terminate)} \]
\[ H(p) = \text{(a program that implements the halting function)} \]

Every programming language provides some way of writing the text that consists of a quotation mark (perhaps by writing it twice, or perhaps by preceding it with a backslash), and I ask you to fill in the definitions of \( q \) and \( Q \) with whatever your favorite programming language uses. Program \( D \) has three text parameters and produces a text result by catenation. For \( T \) choose any program whose execution terminates, and for \( N \) choose any program whose execution does not terminate. And finally, the ability to define \( H \) as a program is the computability assumption.

After these definitions, the program

\[ \text{if } H(D(" \text{if } H(D("",",",") ) \text{ then } N \text{ else } T" )) \text{ then } N \text{ else } T \]

is very interesting because \( H \) is being applied to an argument

\[ D(" \text{if } H(D("",",",") ) \text{ then } N \text{ else } T" )\]

that evaluates to the text representing the program itself. (You should try evaluating this expression to see for yourself.) In other words, the program has the form

\[ \text{if } H(\mathcal{P}) \text{ then } N \text{ else } T \]

where \( \mathcal{P} \) is a text expression whose value represents the program itself. So if execution of this program terminates, then it is equivalent to \( N \) whose execution does not terminate. And if execution of this program does not terminate, then it is equivalent to \( T \) whose execution does terminate. We have an inconsistency. There cannot be any way to define program \( H \).
Semantics Version

In any programming language, all programs are finite sequences of characters, although not all finite sequences of characters are programs. Suppose we have a programming language such that the execution of each program begins by reading a finite sequence of characters as input, and after some computing, does one of three actions:

- writes a 0 as output and then terminates.
- writes a 1 as output and then terminates.
- does not write and does not terminate.

Let $C$ be a finite character set, and let $C^*$ be the set of all finite sequences of characters. Define the mathematical function $\llbracket \rrbracket$ (not a program) called “semantics” as follows.

$$\llbracket p \rrbracket (i) = 0 \text{ if } p \text{ is a program and execution of } p \text{ on input } i \text{ writes } 0 \text{ then terminates}$$

$$1 \text{ if } p \text{ is a program and execution of } p \text{ on input } i \text{ writes } 1 \text{ then terminates}$$

$$2 \text{ if } p \text{ is a program and execution of } p \text{ on input } i \text{ does not write and does not terminate}$$

$$3 \text{ if } p \text{ is not a program}$$

$\llbracket p \rrbracket (i) = 0$ and $\llbracket p \rrbracket (i) = 1$ both include the possibility that execution does not read the entire input, and $\llbracket p \rrbracket (i) = 2$ includes the possibility that execution waits forever for more input.

Define the mathematical function $D$ (not a program) called “diagonal” as follows.

$$D: C^* \rightarrow \{0, 1\}$$

$$D(p) = 0 \text{ if } \llbracket p \rrbracket (p) = 1 \text{ or } \llbracket p \rrbracket (p) = 2 \text{ or } \llbracket p \rrbracket (p) = 3$$

$$1 \text{ if } \llbracket p \rrbracket (p) = 0$$

For all $p$ in $C^*$, $D(p)$ differs from $\llbracket p \rrbracket (p)$, so $D$ is not the semantics of any program. Therefore $D$ is incomputable.

Define the mathematical function $H$ (not a program) called “halting” as follows.

$$H: C^* \rightarrow \{0, 1\}$$

$$H(p) = 0 \text{ if } \llbracket p \rrbracket (p) = 2 \text{ or } \llbracket p \rrbracket (p) = 3$$

$$1 \text{ if } \llbracket p \rrbracket (p) = 0 \text{ or } \llbracket p \rrbracket (p) = 1$$

This halting function reports the halting status for each program on only a single input.

Assume (for contradiction) that $H$ is computable. Then $H$ is the semantics $\llbracket h \rrbracket$ of some program $h$. If the programming language is sufficiently expressive (Turing-Machine equivalent), as every general-purpose programming language is, we can compute $D(p)$ as follows.

Read the input and save it as $p$. Execute $h$ on input $p$, but don't output. If the output from executing $h$ on input $p$ would be 0, output 0. If the output from executing $h$ on input $p$ would be 1, execute $p$ on input $p$, but don't output. If the output from executing $p$ on $p$ would be 0, output 1. If the output from executing $p$ on $p$ would be 1, output 0.

We thus compute $D$. But $D$ is incomputable. Therefore $H$ is incomputable.
Diagonalize-Then-Reduce Version

This is the same as the Semantics Version, but without the semantics function.

In any programming language, all programs are finite sequences of characters, although not all finite sequences of characters are programs. Suppose we have a programming language such that the execution of each program begins by reading a finite sequence of characters as input, and after some computing, does one of three actions:

- writes a 0 as output and then terminates.
- writes a 1 as output and then terminates.
- does not write and does not terminate.

Let \( C \) be a finite character set, and let \( C^* \) be the set of all finite sequences of characters. Define the mathematical function \( D \) (not a program) called “diagonal” as follows.

\[
D: C^* \to \{0, 1\}
\]

\[
D(p) = 1 \text{ if } p \text{ is a program and execution of } p \text{ on input } p \text{ writes } 0 \text{ and then terminates}
\]

\[
D(p) = 0 \text{ otherwise}
\]

\( D(p) = 1 \) includes the possibility that \( p \) is a program and execution of \( p \) on input \( p \) does not read its entire input.

\( D(p) = 0 \) includes the possibility that \( p \) is a program and execution of \( p \) on input \( p \) reads its entire input and waits forever for more input.

Let \( d \) be a program. Does \( d \) implement \( D \)? Implementation means:

- For all \( p \) in \( C^* \), if \( D(p) = 0 \) then execution of \( d \) on input \( p \) writes 0 and terminates.
- For all \( p \) in \( C^* \), if \( D(p) = 1 \) then execution of \( d \) on input \( p \) writes 1 and terminates.

However, if execution of \( d \) on input \( d \) writes 0 and terminates, then \( D(d) = 1 \), not 0. And if execution of \( d \) on input \( d \) writes 1 and terminates, then \( D(d) = 0 \), not 1. So \( d \) does not implement \( D \). Since \( d \) was an arbitrary program, \( D \) is incomputable.

Define the mathematical function \( H \) (not a program) called “halting” as follows.

\[
H: C^* \to \{0, 1\}
\]

\[
H(p) = 1 \text{ if } p \text{ is a program and execution of } p \text{ on input } p \text{ writes } 0 \text{ or } 1 \text{ and then terminates}
\]

\[
H(p) = 0 \text{ otherwise}
\]

This halting function reports the halting status for each program on only a single input.

Assume (for contradiction) that \( H \) is computable. Then \( H \) is implemented by some program \( h \). If the programming language is sufficiently expressive (Turing-Machine equivalent), as every general-purpose programming language is, we can compute \( D(p) \) as follows.

Read the input and save it as \( p \). Execute \( h \) on input \( p \), but don't output. If the output from executing \( h \) on \( p \) would be 0, output 0. If the output from executing \( h \) on \( p \) would be 1, execute program \( p \) on input \( p \), but don't output. If the output from executing \( p \) on \( p \) would be 0, output 1. If the output from executing \( p \) on \( p \) would be 1, output 0.

We thus compute \( D \). But \( D \) is incomputable. Therefore \( H \) is incomputable.
General Diagonalize-Then-Reduce Version

This is the same as Diagonalize-Then-Reduce but with a more realistic range of programs.

Choose a programming language. All programs in that language are finite sequences of characters, although not all finite sequences of characters are programs. Execution of a program may read a sequence of characters as input, and may write a sequence of characters as output. Reading does not have to precede writing; they can be mixed. The input sequence may be empty, or a finite number of characters, or an infinite number of characters. Likewise the output sequence. Execution may terminate, or it may run forever.

Let $C$ be a finite character set, and let $C^*$ be the set of all finite sequences of characters. Define the mathematical function $D$ (not a program) called “diagonal” as follows.

\[
D: C^* \rightarrow \{\text{“red”}, \text{“blue”}\}
\]
\[
D(p) = \text{“red”} \text{ if } p \text{ is a program and execution of } p \text{ on input } p \text{ writes “blue” and then terminates}
\]
\[
D(p) = \text{“blue”} \text{ otherwise}
\]

Let $d$ be a program. Does $d$ implement $D$? Implementation means:

- For all $p$ in $C^*$, if $D(p) = \text{“red”}$ then execution of $d$ on input $p$ writes “red” and terminates.
- For all $p$ in $C^*$, if $D(p) = \text{“blue”}$ then execution of $d$ on input $p$ writes “blue” and terminates.

However, if execution of $d$ on input $d$ writes “red” and terminates, then $D(d) = \text{“blue”}$, not “red”. And if execution of $d$ on input $d$ writes “blue” and terminates, then $D(d) = \text{“red”}$, not “blue”. So $d$ does not implement $D$. Since $d$ was an arbitrary program, $D$ is incomputable.

Define the mathematical function $H$ (not a program) called “halting” as follows.

\[
H: C^* \rightarrow \{\text{“yes”}, \text{“no”}\}
\]
\[
H(p) = \text{“yes”} \text{ if } p \text{ is a program and execution of } p \text{ on input } p \text{ terminates}
\]
\[
H(p) = \text{“no”} \text{ otherwise}
\]

This halting function reports the halting status for each program on only a single input. $H(p) = \text{“yes”}$ includes the possibility that $p$ is a program and execution of $p$ does not read the entire input $p$. $H(p) = \text{“no”}$ includes the possibility that $p$ is a program and execution of $p$ reads the entire input $p$ and waits forever for more input.

Assume (for contradiction) that $H$ is computable. Then $H$ is implemented by some program $h$. If the programming language is sufficiently expressive (Turing-Machine equivalent), as every general-purpose programming language is, we can compute $D(p)$ as follows.

Read the input and save it as $p$. Execute $h$ on input $p$, but don't output. If the output from executing $h$ on $p$ would be “no”, output “blue”. If the output from executing $h$ on $p$ would be “yes”, execute program $p$ on input $p$, but don't output. If the output from executing $p$ on $p$ would be “blue”, output “red”. If the output from executing $p$ on $p$ would be anything other than “blue”, output “blue”.

We thus compute $D$. But $D$ is incomputable. Therefore $H$ is incomputable.
Simpler Diagonalize-Then-Reduce Version

In any programming language, all programs are finite sequences of characters, although not all finite sequences of characters are programs. Suppose we have a programming language such that the execution of each program reads a finite sequence of characters as input, and either terminates, or computes forever.

Let $C$ be a finite character set, and let $C^*$ be the set of all finite sequences of characters. Define the mathematical function $H$ (not a program) called “halting” as follows.

$$H: C^* \rightarrow \{0, 1\}$$

$$H(p) = 1 \text{ if } p \text{ is a program and execution of } p \text{ on input } p \text{ terminates}$$
$$0 \text{ otherwise}$$

This halting function reports the halting status for each program on only a single input. $H(p) = 1$ includes the possibility that $p$ is a program and execution of $p$ terminates before reading the entire input $p$. $H(p) = 0$ includes the possibility that $p$ is a program and execution of $p$ reads the entire input $p$ and waits forever for more input. $H(p) = 0$ also includes the possibility that $p$ is not a program.

Is there a program $d$ with the following behavior? For all $p$ in $C^*$,

- if $H(p) = 0$ then execution of $d$ on input $p$ terminates.
- if $H(p) = 1$ then execution of $d$ on input $p$ does not terminate.

If execution of $d$ on input $d$ terminates, then $H(d) = 1$, not 0. And if execution of $d$ on input $d$ does not terminate, then $H(d) = 0$, not 1. So the specification of $d$ is inconsistent; there is no such program.

Assume (for contradiction) that $H$ is computable. Then $H$ is implemented by some program $h$. If the programming language is sufficiently expressive (Turing-Machine equivalent), as every general-purpose programming language is, we can write program $d$ as follows.

Read the input and save it as $p$. Execute $h$ on input $p$, but don't output. If the output from executing $h$ on $p$ would be 0, terminate execution. If the output from executing $h$ on $p$ would be 1, loop forever.

But there is no such program. Therefore $H$ is incomputable.