

The Geometry of \mathbf{C}^n is Important for the Algebra of Elementary Functions

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1 What do I mean by “Algebra”

I refer to the algebra of elementary functions, but not viewed as abstract solutions of differential equations, so that

$$(\ln f)' = \frac{f'}{f}; \quad (\exp f)' = f' \exp f \quad (1)$$

which only define the functions “up to a constant”.

Instead we want to reason with these functions as genuine one-valued functions $\mathbf{C} \rightarrow \mathbf{C}$, or even $\mathbf{R} \rightarrow \mathbf{R}$. Contrast

$$\ln z = w : e^w = z \text{ and } -\pi < \Im w \leq \pi.$$

$$\text{Ln } z = \{w : e^w = z\} = \{\ln z + 2n\pi i \mid n \in \mathbf{Z}\}.$$

For the purposes of this paper, the precise definitions of \ln , \arctan etc. as functions $\mathbf{C} \rightarrow \mathbf{C}$ (or $\mathbf{R} \rightarrow \mathbf{R}$) is that given in [5], which repeats, with more justification, the definitions of [1]. In particular, the branch cut of \ln (and $\sqrt{\quad}$) is along the negative real axis, with the negative axis itself being continuous with the upper half-plane, so that $\lim_{\epsilon \rightarrow 0^+} \ln(-1 + \epsilon i) = i\pi = \ln(-1)$, but $\lim_{\epsilon \rightarrow 0^-} \ln(-1 + \epsilon i) = -i\pi \neq \ln(-1)$.

We consider a variety of potential equations involving elementary functions. $\sqrt{z^2} \stackrel{?}{=} z$ is one: it is patently false, even over \mathbf{R} , with $z = -1$ as a counterexample. Note that $\text{Sqrt}(z^2) = \{\pm z\}$. Another pseudo-equation is

$$\ln \bar{z} \stackrel{?}{=} \overline{\ln z} : \quad (2)$$

this is false on the branch cut for \log , and instead $\ln \bar{z} = \overline{\ln z} + 2\pi i$ on the cut. Similarly,

$$\ln\left(\frac{1}{z}\right) \stackrel{?}{=} -\ln z \quad (3)$$

is false on the branch cut: instead $\ln\left(\frac{1}{z}\right) = -\ln z + 2\pi i$ on the cut. Note that $\text{Ln}\left(\frac{1}{z}\right) = -\text{Ln}(z)$ (interpreted element-wise) and so on.

Another pseudo-equation that causes problems over the reals as well as over the complexes is

$$\arctan(x) + \arctan(y) \stackrel{?}{=} \arctan\left(\frac{x+y}{1-xy}\right). \quad (4)$$

2 How to handle multi-valued functions

[6] and [3] discuss various treatments of the inherently multi-valued functions such as $\sqrt{\quad}$, \ln and \arctan . The four approaches are given in the following sub-sections.

2.1 Signed zeros

This goes back to work of Kahan [10, 9], and distinguishes 0^+ from 0^- . This technique can resolve the issues raised by $\ln \bar{z}$ and $\ln \frac{1}{z}$, provided that we state that $\ln(-1 + 0^+i) = i\pi$ but $\ln(-1 + 0^-i) = -i\pi$. Effectively we have a double cover of the branch cut. This method is no help in those situations where the pseudo-equation is invalid on a set of measure greater than 0, such as $\sqrt{z^2}$ and the \arctan addition example.

2.2 Genuinely exact equations

[8] claim that the most fundamental failure is $z \stackrel{?}{=} \ln \exp z$. They therefore introduce the unwinding number, \mathcal{K} , defined by

$$\mathcal{K}(z) = \frac{z - \ln \exp z}{2\pi i} = \left\lceil \frac{\Im z - \pi}{2\pi} \right\rceil \in \mathbf{Z}. \quad (5)$$

The problem with $\ln \frac{1}{z}$ is then rescued as:

$$\ln \frac{1}{z} = -\ln z - 2\pi i \mathcal{K}(-\ln(z)). \quad (6)$$

They would write the \arctan addition equation as:

$$\arctan(x) + \arctan(y) = \arctan\left(\frac{x+y}{1-xy}\right) + \pi \mathcal{K}(2i(\arctan(x) + \arctan(y))). \quad (7)$$

2.3 Multi-valued functions

Mathematical texts often urge us to treat these functions as multi-valued, defining $\text{Arctan}(x) = \{y \mid \tan x = y\}$. In this interpretation, the arctan addition equation, considered as

$$\text{Arctan}(x) + \text{Arctan}(y) \stackrel{?}{=} \text{Arctan}\left(\frac{x+y}{1-xy}\right),$$

with the $+$ on the left-hand side representing element-by-element addition of sets, is valid.

In general, all the “algebraic” rules of simplification are valid in this context, e.g. with $\text{Sqrt}(x) = \{y \mid y^2 = x\} = \{\pm\sqrt{x}\}$, it is the case that

$$\text{Sqrt}(x)\text{Sqrt}(y) = \text{Sqrt}(xy). \quad (8)$$

There are a few caveats that must be mentioned, though.

1. Cancellation is no longer trivial, since in principle $\text{Arctan}(x) - \text{Arctan}(x) = \{n\pi \mid n \in \mathbf{Z}\}$, rather than being zero.
2. Not all such multivalued functions have such simple expressions as

$$\text{Arctan}(x) = \{\arctan(x) + n\pi \mid n \in \mathbf{Z}\}.$$

$$\text{Arcsin}(x) = \{\arcsin(x) + 2n\pi \mid n \in \mathbf{Z}\} \cup \{\pi - \arcsin(x) + 2n\pi \mid n \in \mathbf{Z}\}.$$

- These problems combine, so that, if $A = \text{Arcsin}(x)$,

$$\begin{aligned} A - A &= \{2n\pi \mid n \in \mathbf{Z}\} \cup \{2\arcsin(x) - \pi + 2n\pi \mid n \in \mathbf{Z}\} \\ &\quad \cup \{\pi - 2\arcsin(x) + 2n\pi \mid n \in \mathbf{Z}\} \\ &= \{2n\pi \mid n \in \mathbf{Z}\} + \{0, 2\arcsin(x) - \pi, \pi - 2\arcsin(x)\}. \end{aligned}$$

Note that this still depends on x , unlike the case of $\text{Arctan}(x) - \text{Arctan}(x)$.

In the case of non-elementary functions, as in the Lambert W function, there may be no simple relationship between different branches.

3. However, some equations take on somewhat surprising forms in this context, e.g. the hypothetical $\arcsin(z) \stackrel{?}{=} \arctan\left(\frac{z}{\sqrt{1-z^2}}\right)$, simply becomes the correct

$$\text{Arcsin}(z) \subset \text{Arctan}\left(\frac{z}{\text{Sqrt}(1-z^2)}\right), \quad (9)$$

and if we want an equality of sets, we have

$$\text{Arcsin}(z) \cup \text{Arcsin}(-z) = \text{Arctan}\left(\frac{z}{\text{Sqrt}(1-z^2)}\right), \quad (10)$$

in which both sides take on four values in each 2π period. It is an open question to produce an alternative characterisation of just $\text{Arcsin}(z)$.

Table 1: Decomposition of complex plane for $\sqrt{z^2}$

Region	$\Re(z)$	$\Im(z)$	$\sqrt{z^2}$
R_1	< 0	—	$-z$
R_2	$= 0$	< 0	$-z$
R_3	$= 0$	$= 0$	$z = -z$
R_4	$= 0$	> 0	z
R_5	> 0	—	z

4. The equation

$$\text{Log}(z^2) = 2 \text{Log}(z) \quad (11)$$

is not valid if we interpret $2 \text{Log}(z)$ as $\{2y \mid \exp(y) = z\}$, since this has an indeterminacy of $4\pi i$, and the left-hand side has an indeterminacy of $2\pi i$. Instead we need to interpret $2 \text{Log}(z)$ as $\text{Log}(z) + \text{Log}(z)$, and under this interpretation, the equation is true, as a specialisation of the correct equation

$$\text{Log}(z_1 z_2) = \text{Log}(z_1) + \text{Log}(z_2). \quad (12)$$

5. Pseudo-equations in which ambiguity disappears, such as $\sqrt{z^2} \stackrel{?}{=} z$, cannot be encoded as $\text{Sqrt}(z^2) = z$, since this is trying to equate a set and a number, but rather have to be encoded as $z \in \text{Sqrt}(z^2)$.

2.4 Riemann surfaces

It is often said that one should “consider the Riemann surface”. Unfortunately, in the case of the arctan addition equation, $\arctan x$ is defined on one surface, $\arctan y$ on a second, and $\arctan\left(\frac{x+y}{1-xy}\right)$ on a third. It is not clear how “considering the Riemann surface” solves practical questions such as this identity.

3 Consider $\sqrt{z^2}$

It follows from multiplying Sqrts that $(\text{Sqrt}(z))^2 = \text{Sqrt}(z^2)$. Since $z = (\sqrt{z})^2$, this means that $z \in \text{Sqrt}(z^2)$, i.e. $z = \pm\sqrt{z^2}$. The question then resolves to “plus or minus”, or, in line with the thesis of this paper, “where on \mathbf{C} is it plus, and where is it minus”?

\sqrt{z} has its branch cut on the negative real axis, more precisely on $(-\infty, 0]$. Therefore the branch cut relevant to $\sqrt{z^2}$ is when $z^2 \in (-\infty, 0]$, i.e. $z \in [0, i\infty)$ or $z \in (-i\infty, 0]$. Note that it is not correct to write $z \in [0, i\infty) \cup (-i\infty, 0] = (-i\infty, i\infty)$. Therefore the complex plane is divided into five regions, as shown in the table.

This case analysis can be reduced (though there is no known algorithm for doing this) to $\sqrt{z^2} = \text{csgn}(z)z$, which can also be expressed as

$$\sqrt{z^2} = (-1)^{\mathcal{K}(2 \ln z)} z. \quad (13)$$

4 Consider $\ln \frac{1}{z}$ and $\ln \bar{z}$

These are very similar, and we will only deal with $\ln \frac{1}{z}$ in detail. The branch cut for $\ln z$ is along the negative real axis $(\infty, 0)$, which is transformed into itself by $z \mapsto \frac{1}{z}$, and so is also the branch cut for $\ln \frac{1}{z}$. This does not disconnect the complex plane, so there are only two cases: on the cut and off it. We know that $\ln \frac{1}{z} \in -\text{Log}(z)$, so the only corrections required to make this equation valid for single-valued functions are by adding multiples of $2\pi i$. Off the branch cut, an evaluation at $z = 1$ shows that no correction is necessary, whereas an evaluation at -1 shows that, on the branch cut, a correction of $2\pi i$ is necessary. If we wish, we can write this as

$$\ln \frac{1}{z} = -\ln z - 2\pi i \mathcal{K}(-\ln z). \quad (14)$$

5 Additivity of arctan

In this section, we investigate the arctan addition pseudo-equation and attempt an algorithmic correction to it.

If we differentiate both sides of this equation with respect to x , we get

$$\frac{1}{1+x^2} \stackrel{?}{=} \frac{1}{1+x^2},$$

which is true, and if we differentiate both sides with respect to y , we get

$$\frac{1}{1+y^2} \stackrel{?}{=} \frac{1}{1+y^2},$$

which is also true.

Hence the difference between the two sides is a local constant, in the sense that its derivatives are zero, and so, between jumps, it is constant. Evaluating both sides of this equation at $x = y = 0$, we get 0 on both sides, so we conclude that here, the difference is indeed zero, so that this equation is indeed (locally) an identity. However, if we do the same at $x = 1.2$, $y = 0.9$, we get

$$1.608873152\dots \stackrel{?}{=} 1.532719501\dots :$$

clearly not valid, and indeed wrong by π .

5.1 $\mathbf{R} \rightarrow \mathbf{R}$

It is not obvious why there is a problem here, since arctan is a continuous, differentiable function, even bijection, $(-\infty, \infty) \rightarrow (-\pi/2, \pi/2)$. We can define $\arctan(-\infty) = -\pi/2$, $\arctan(\infty) = \pi/2$ to get a bijection $[-\infty, \infty] \rightarrow [-\pi/2, \pi/2]$.

Table 2: Cylindrical Decomposition of (x, y) -plane

x	xy	dimension	correction
> 0	> 1	2	π
> 0	$= 1$	1	0
> 0	< 1	2	0
$= 0$	—	1	0
< 0	> 1	2	$-\pi$
< 0	$= 1$	1	$-\pi$
< 0	< 1	2	0

Unfortunately, $[-\infty, \infty]$ is not the right domain for this sort of analysis. One way of seeing this is to observe that, although $(-\infty, \infty) = \mathbf{R} \subset \mathbf{C}$, the analytic completion of \mathbf{C} is the one-point completion $\mathbf{C} \cup \{\infty\}$, and $[-\infty, \infty] \not\subset \mathbf{C} \cup \{\infty\}$.

In fact, \arctan has a branch cut at infinity. When $x = \infty$ (or $y = \infty$), this might seem to cause a problem, since $\frac{x+y}{1-xy}$ tends to $\frac{-1}{y}$. However, the problem this causes is masked by the another, more serious, problem.

It is possible for $\frac{x+y}{1-xy}$ to pass through ∞ even when both x and y are finite, namely when $xy = 1$. If $\frac{x+y}{1-xy}$ goes from “large and positive” to “large and negative”, then π is subtracted from the value of its \arctan , and *vice versa*. We need to add a correction term, which can be done in various ways, e.g.

$$\arctan(x) + \arctan(y) = \arctan\left(\frac{x+y}{1-xy}\right) + \begin{cases} \pi & x > 0, xy > 1 \\ 0 & x \geq 0, xy \leq 1 \\ 0 & x < 0, xy < 1 \\ -\pi & x < 0, xy \geq 1 \end{cases} \quad (15)$$

The equation

$$\arctan(x) + \arctan(y) = \arctan\left(\frac{x+y}{1-xy}\right) + \pi \mathcal{K}(2i(\arctan(x) + \arctan(y))). \quad (16)$$

is in one sense only another way of saying the same thing, except that it is coupled more clearly to the problem of “overflow” in adding the two \arctan terms, and the boundary cases are dealt with consistently.

The expression with cases divides the (x, y) -plane into three regions (the two entries with zero correction term define one region, open on the lower-left boundary and closed on the top-right boundary. If we proceed algorithmically, by cylindrical algebraic decomposition, we in fact decompose the plane into seven regions, as given in the table.

The technique of clustering would reduce this, ideally to three regions, but certainly to five regions, which we will describe as follows.

One interesting question is the extent to which the r.h.s. with cases can be reconstructed automatically. Evaluation at $x = y = 0$ shows that the naive equation is true there, and therefore throughout R_1 . Similarly, evaluation at $x = y = 1$ shows that it is true there, and so throughout R_2 . Evaluation at

Table 3: 5 Regions of the (x, y) -plane

	R_1	R_2	R_3	R_4	R_5
xy	< 1	$= 1$	$= 1$	> 1	> 1
x	$-$	> 0	< 0	> 0	< 0

$x = y = -1$ shows that the naive equation is false, and needs a correction factor of $-\pi$ at that point, and therefore throughout R_3 . By hand, evaluation at $x = y = 2$ shows that the naive equation is false, and needs a correction factor of π at that point, and therefore throughout R_4 . However, it seems impossible to persuade Maple (release V.5) to simplify $2 \arctan 2 + \arctan \frac{4}{3}$ to π . *Mutatis mutandis*, the same remarks apply to $x = y = -2$ and R_5 . Of course, the author has chosen values of x and y at which the arctan function has a simple expression, and how could an algorithm do that?

The answer is that it need not. Since we know that $\arctan(x) + \arctan(y) \in \text{Arctan}\left(\frac{x+y}{1-xy}\right)$, any error has to be a multiple of π . So a (sufficiently careful) numerical evaluation is all that is needed.

5.2 $\mathbb{C} \rightarrow \mathbb{C}$

The definition of $\arctan x$ is [1, 5]

$$\frac{1}{2i} (\ln(1 + ix) - \ln(1 - ix)).$$

Hence its branch cuts in the complex plane are along $1 + ix \in (-\infty, 0]$, i.e. $x \in [i, i\infty)$, and along $1 - ix \in (-\infty, 0]$, i.e. $x \in (-i\infty, -i]$. These do not disconnect the complex plane, so the only special cases are along them. The same is true of $\arctan y$ and $\arctan\left(\frac{x+y}{1-xy}\right)$. There is still the critical locus $xy = 1$, as in the real case.

We now have to determine how these interact. Write $x = x_R + ix_I$ etc. Then we have to consider various interesections.

- The intersection of the two branch cuts for $\arctan x$ and $\arctan y$, This is clearly possible, since the two constraints are independent.
- The intersection of the branch cuts for $\arctan\left(\frac{x+y}{1-xy}\right)$ with the branch cuts for $\arctan x$. If one solves for the two (real) equations resulting from $\Re\left(\frac{x+y}{1-xy}\right) = 0$ and $x_R = 0$, one is left with, *inter alia*, the resultant

$$-3y_R y_I^2 - y_I^6 y_R - 3y_I^2 y_R^5 - 3y_I^4 y_R^3 - y_R^7 + y_R + y_R^3 + 2y_R^3 y_I^2 - y_R^5 + 3y_I^4 y_R. \quad (17)$$

The only solutions of this have $|y_R| \leq 1$ and $|y_I| \leq 1$, and therefore are not on the branch cut for $\arctan y$, except that when $y_R = 0$, y_I is unconstrained. Hence it is in fact possible to be on all the branch cuts of \arctan simultaneously, say with $x = y = 2i$, and $\frac{x+y}{1-xy} = \frac{-4}{3}i$.

- The intersection of the branch cuts for $\frac{x+y}{1-xy}$ with the branch cuts for $\arctan x$. This is identical to the previous case.
- The intersection of the branch cut for $\arctan x$ with the critical locus $xy - 1$. It then follows that y_R has to be zero (since $x_I y_R = 0$), so the point is also on the branch cut of $\arctan y$, and possibly on the branch cut for $\arctan\left(\frac{x+y}{1-xy}\right)$.
- The intersection of the branch cut for $\arctan\left(\frac{x+y}{1-xy}\right)$ with the critical locus $xy - 1$ cannot happen.

In sum, the situation here is very complicated, but can be reduced to a finite number of regions which need to be tested. It in fact turns out that the move to the complex plane does not, in fact, add any further complication.

The unwinding number approach tells us easily that the correction is

$$-\pi\mathcal{K}\left(\ln(1+ix) - \ln(1-ix) + \ln(1+iy) - \ln(1-iy) + \right. \quad (18)$$

$$\left. \ln\left(1 + \frac{i(x+y)}{1-xy}\right) - \ln\left(1 - \frac{i(x+y)}{1-xy}\right)\right) \quad (19)$$

but there seems to be no easy simplification of this.

6 Strategies for simplifying

Traditionally, computer algebra systems, and indeed humans, are bad at simplifying expressions containing the (inverse) elementary functions. Humans fail to spot special cases, often with serious consequences, and computer algebra writers are torn between:

- being careful, as in Maple's `simplify(...)`, and therefore failing to make correct simplifications such as $\sqrt{1-z}\sqrt{1+z} \rightarrow \sqrt{1-z^2}$;
- using the full range of algebraic rules, as in Maple's `simplify(...,symbolic)`, and therefore making incorrect simplification such as $\sqrt{z^2} \rightarrow z$.

We now describe two strategies (at the current state of development, it would not be accurate to describe them as algorithms), based on the views and examples above.

6.1 The Unwinding Number Approach

This approach, outlined in [3, 6], works as follows.

While a reduction exists

Perform a reduction

Generally introducing unwinding numbers

Remove as many unwinding numbers as possible

See if case-by-case analysis removes unwinding numbers

For example, the correct rule for multiplying square roots would be

$$\sqrt{x}\sqrt{y} = \sqrt{xy}(-1)^{K(\ln x + \ln y)}. \quad (20)$$

An illustration of this method would be the following proof from [6].

Lemma 1 *Whatever the value of z ,*

$$\sqrt{1-z}\sqrt{1+z} = \sqrt{1-z^2}.$$

Proof. It is sufficient to show that the unwinding number term in the rule for multiplying square roots is zero. Whatever the value of z , $1+z$ and $1-z$ have imaginary parts of opposite signs. Without loss of generality, assume $\Im z \geq 0$. Then $0 \leq \arg(1+z) \leq \pi$ and $-\pi < \arg(1-z) \leq 0$. Therefore their sum, which is the imaginary part of $\ln(1+z) + \ln(1-z)$, is in $(-\pi, \pi]$. Hence the unwinding number is indeed zero.

Note the manual reasoning required to remove the unwinding number term that the rule introduced.

6.2 The “Regions of Validity” Approach

This approach, used informally in the previous sections, works as follows.

Let E' be the multi-valued version of E .

While a reduction of E' exists

reduce E' to yield a new E'

Let E'' be the single-valued version of the reduced E' .

Analyse \mathbf{C}^n to determine corrections required to $E \stackrel{?}{=} E''$.

This method would prove the lemma the following way.

Proof. $E' := \text{Sqrt}(1-z)\text{Sqrt}(1+z)$. This reduces to $\text{Sqrt}(1-z^2)$, so we know that $\sqrt{1-z}\sqrt{1+z} \in \text{Sqrt}(1-z^2)$. Hence we have to analyse $\sqrt{1-z}\sqrt{1+z} \stackrel{?}{=} \sqrt{1-z^2}$. The relevant branch cuts are as follows.

For $\sqrt{1-z}$: $1-z \in (-\infty, 0]$, so $z \in [1, \infty)$.

For $\sqrt{1+z}$: $1+z \in (-\infty, 0]$, so $z \in (-\infty, -1]$.

For $\sqrt{1-z^2}$: $1-z^2 \in (-\infty, 0]$, so $z^2 \in [1, \infty)$, and $z \in [1, \infty)$ or $z \in (-\infty, -1]$.

These branch cuts do not disconnect the complex plane, so the three regions are $[1, \infty)$, $(-\infty, -1]$ and the rest of the plane.

$[1, \infty)$ Take $z = 3$. Then $\sqrt{1-z}\sqrt{1+z} = \sqrt{-2}\sqrt{4} = 2\sqrt{2}i$. $\sqrt{1-z^2} = \sqrt{-8} = 2\sqrt{2}i$, so no correction is needed.

$(-\infty, -1]$ Take $z = -3$. Then $\sqrt{1-z}\sqrt{1+z} = \sqrt{4}\sqrt{-2} = 2\sqrt{2}i$. $\sqrt{1-z^2} = \sqrt{-8} = 2\sqrt{2}i$, so no correction is needed.

rest of plane Take $z = i$. Then $\sqrt{1-z}\sqrt{1+z} = \sqrt{1-i}\sqrt{1+i} = \sqrt{2}$ (clearly the correct norm, and the arguments cancel). $\sqrt{1-z^2} = \sqrt{2}$, so again no correction is necessary.

Note that, while it might appear that some intelligence was used to select the sample values, any sample value s such that $\sqrt{1-s^2} \neq -\sqrt{1-s^2}$ would do, as long as we evaluated $\sqrt{1-s}\sqrt{1+s}$ to enough precision to be sure which of the two values it was taking.

7 Strategies to Algorithms?

In this section, we explore what would be necessary to convert the strategies outlined above into complete (and possibly even efficient) algorithms.

7.1 The Unwinding Number Approach

A prime requirement of this method is a complete set of *correct* transformation rules. Thus, instead of the incorrect equation $\sqrt{x}\sqrt{y} \stackrel{?}{=} \sqrt{xy}$, we need the correct equation $\sqrt{x}\sqrt{y} = \sqrt{xy}(-1)^{K(\ln x + \ln y)}$. While not conceptually very difficult, to my knowledge no such complete list has been built up. It would have to include rules for “incorrect” applications of inverse functions, so that the incorrect $z \stackrel{?}{=} \ln \exp z$ becomes the correct $z = \ln \exp z + 2\pi i\mathcal{K}(z)$. The often-quoted, but incorrect equation

$$\arcsin z \stackrel{?}{=} \arctan \frac{z}{\sqrt{1-z^2}} \quad (21)$$

has to be replaced by

$$\arcsin z = \arctan \left(\frac{z}{\sqrt{1-z^2}} \right) + \pi\mathcal{K}(-\ln(1+z)) - \pi\mathcal{K}(-\ln(1-z)). \quad (22)$$

Another obstacle is the tendency for expressions involving \mathcal{K} to proliferate: in the course of proving this equation, they had to handle equations such as the following.

$$\begin{aligned} 2i \arctan \left(\frac{z}{\sqrt{1-z^2}} \right) &= 2i \arcsin(z) \\ &\quad - 2\pi i\mathcal{K} \left(2 \ln \left(iz + \sqrt{1-z^2} \right) \right) \\ &\quad + 2\pi i\mathcal{K} \left(\ln \left(1 + i \frac{z}{\sqrt{1-z^2}} \right) - \ln \left(1 - i \frac{z}{\sqrt{1-z^2}} \right) \right). \end{aligned}$$

The third problem is that of understanding the result, which in this case means reducing

$$- \pi\mathcal{K} \left(2 \ln \left(iz + \sqrt{1-z^2} \right) \right) + \pi\mathcal{K} \left(\ln \left(1 + i \frac{z}{\sqrt{1-z^2}} \right) - \ln \left(1 - i \frac{z}{\sqrt{1-z^2}} \right) \right)$$

to $\pi\mathcal{K}(-\ln(1+z)) - \pi\mathcal{K}(-\ln(1-z))$. This may well result in a difficult case-by-case analysis, so there may be no useful overall picture.

7.2 The “Regions of Validity” Approach

In this approach, the first problem is also that of finding a “correct” set of equations, in this case replacing the incorrect equation $\sqrt{x}\sqrt{y} \stackrel{?}{=} \sqrt{xy}$ by the equality of sets in $\text{Sqrt}(x)\text{Sqrt}(y) = \text{Sqrt}(xy)$. While not conceptually very difficult, to my knowledge no complete list of such equations has been built up. It would have to include rules for “incorrect” applications of inverse functions, so that the incorrect $z \stackrel{?}{=} \ln \exp z$ becomes the correct $z \in \text{Log exp } z$.

One problem, though, is that not all simplification rules remain set equalities, as in the equation between \arcsin and \arctan . Provided the strategy only expands E' , then no real harm is done, but it must never contract it. There is also a problem with equations such as $z \in \text{Sqrt}(z^2)$. It does not seem to be trivial to make an algorithm out of this.

Handling the decompositions of \mathbf{R}^{2n} (as we see \mathbf{C}^n) is also difficult. The existing technology of cylindrical algebraic decomposition [4] has the following defects when applied to the problem at hand.

- It does not handle directly descriptions such as the branch cut for \ln , i.e. $\Re(z) < 0 \& \Im(z) = 0$. Instead one has to introduce the two planes $\Re(z) = 0$ and $\Im(z) = 0$, even though $\Re(z) = 0$ is irrelevant off $\Im(z) = 0$.
- As has been remarked by many authors, even for the original purposes of quantifier elimination, cylindrical algebraic decomposition is *too* powerful, since it solves not only the question at hand, but also all other questions relating to the same set of equations.
- The algorithm produces far too many regions. This can partly be solved by the technique of clustering [2], but this is a retrospective technique (produce too many, then reduce), and there is no work on how this interacts with the first problem.

7.3 Putting it all together

Assuming that we eventually want an identity relating single-valued functions, what is the simplest way of expressing it? Our equation

$$\arcsin z = \arctan\left(\frac{z}{\sqrt{1-z^2}}\right) + \pi\mathcal{K}(-\ln(1+z)) - \pi\mathcal{K}(-\ln(1-z)).$$

is hardly simple, but is it any better as

$$\arcsin z = \overline{\arctan\left(\frac{z}{\sqrt{1-z^2}}\right)}? \tag{23}$$

The latter does not easily imply that, almost everywhere, $\arcsin z = \arctan\left(\frac{z}{\sqrt{1-z^2}}\right)$, whereas, once used to reading formulae involving \mathcal{K} , the former does.

If we have an analysis in terms of cases, is there any algorithmic reconstruction in terms of \mathcal{K} ? None is known, and it is worth pointing out that one can

also produce “nonsense” justifications in terms of \mathcal{K} , e.g. the cases of $\ln \frac{1}{z}$ and $\ln \bar{z}$ can be combined to give the correct, but unhelpful

$$\ln \frac{1}{z} = -\ln z - 2\pi i \mathcal{K}(\overline{\ln z}). \quad (24)$$

8 Conclusion

There are several forms of “identities” relating complex-valued (or even real-valued) elementary functions.

1. Those that are true, and easily provable to be so. This class has not had much mention in this paper, but, in particular, all identities involving forward functions (exp, trigonometric and hyperbolic functions, raising to integer powers) only are correct, as are those in which inverse functions are applied correctly.
2. Those that are true, but whose naive proof is false. A good example of this is the lemma on $\sqrt{1-z}\sqrt{1+z}$ where the naive proof by multiplying out square roots needs a lot of help to make it correct. These are the ones that computer algebra systems ought to get *reliably*, but currently cannot.
3. Those that are “almost true”. $\ln \frac{1}{z}$ and $\ln \bar{z}$ are good examples of this. In a numerical context, these can effectively be taken as true, since the chance of landing on an exception value is very small, and an adaptive solver will increase the sampling density near the exceptional value to reduce its impact. In some numerical contexts, signed zeros will obviate the problem. In computer algebra, there is no such excuse: the answer given is wrong. However, not warning the user that there is an “almost good enough” simplification is unhelpful, to say the least. As we saw, sometimes these can be re-written by means of a “double conjugate” trick.
4. Those that are only partially true, i.e. only true on some subset, of measure less than one, of the argument range. $\sqrt{z^2} \stackrel{?}{=} z$ and

$$\arctan(x) + \arctan(y) \stackrel{?}{=} \arctan\left(\frac{x+y}{1-xy}\right)$$

are good examples of this.

Computer algebra systems currently give no help with the third and fourth type of “identity”, or in distinguishing them from the second. The techniques outlined in this paper are, it is hoped, a start in filling this gap.

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