

# A Formal Analysis of Iterative TDD

## Authors

Hemil Ruparel ( [hemilruparel2002@gmail.com](mailto:hemilruparel2002@gmail.com) )

Nabarun Mondal ( [nabarun.mondal@gmail.com](mailto:nabarun.mondal@gmail.com) )

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## About

This document was created over authors discussing measurable efficacy of modern development practices. These discussions triggered a now famous LinkedIn post which got eventually shared by Kent Beck. Arguably, the formalism in that post needed a lot more work. In this paper we try to semi formally present the argument for Test Driven Development ( TDD ) and the reason behind it's efficacy. We also caution against the cargo cult development which is happening in the name of TDD which can be demonstrated to be not effective.

## Abstract

We first introduce some concepts. Following concepts gets formally defined :

1. Functions as Point Mapping
2. Software as functions
3. Tests as higher order functions
4. Equivalence Partitions
5. Coupling in Software

Based on these we argue about the nature of the software development in terms of TDD and TDD gets formally defined for the first time in the history of TDD.

In the next section we showcase the context in which TDD provably works.

We then argue from current development trends that TDD is definitely not being used in such narrow provable context.

We conclude by stating while evidently it can not work except in narrow contexts, that is the best tool we have when applied in those right contexts - e.g Unit Like Tests where implementation has almost non existent coupling.

## Definitions

### Specification of Functions via Point Pairs

Any function, computable or not, can be imagined to be pairs ( potentially  $\aleph_1$  ) of input and output points in some abstract space. It makes sense to describe functions by defining their specific outputs at specific points or a large set of equivalent points. This list of pairs we shall call point specification or "specification" for brevity.

For functions which are well behaved this makes some sense. But even for well behaved functions this is not a good enough approximation.

Take a nice function like  $f(x) = x$  , a tautology but one can not define this function by adding pairs of specification values. A much more interesting function like  $f(x) = \sin(x)$  is much harder to describe, although we can always define them pointwise, and that would ensure the resulting "sampling" looks much and much like the target function, one must understand infinite pairs would be required to specify  $\sin(x)$ . Even with  $\aleph_0$  points specified, there would be set of infinite functions who are not  $\sin(x)$  but just gives off the exact same value at all those specific points. This has a name, called pointwise convergence.

Outside those fixed set of points the family of functions can take arbitrary values - and thus specification via point pairs arguably pose a problem.

Luckily, for software we can do much better, which is the topic for the next section.

## Software

A software is defined to be a Computable Function - mapping abstract vector space of input to the output vector space. The notion of using vectors is due to all real software works with many inputs and hence the state space is multidimensional which is the exact same space as output.

$$S : \hat{I} \rightarrow \hat{O}$$

where  $\hat{I} := < x_i >$  is the input vector while  $\hat{O} := < y_j >$  is the output vector. These vectors are defined not in physics sense, but pure mathematical sense. The only change between the pointwise defined function vs specified software is about being "Computable".

# Software Test

A "Software" test is defined as a higher order function :

$$T : t < \hat{I}_t, S_t, \hat{O}_e > \rightarrow S_t(\hat{I}_t) = \hat{O}_t$$

In plain English, a test is comprise of Input vector  $\hat{I}_t$ , the software under test  $S_t$ , and the expected output vector  $\hat{O}_t$  , it runs the  $S_t$  with the input, and checks whether or not the expected output  $\hat{O}_t$  matches against the actual output of the system :

$$S_t(\hat{I}_t) = \hat{O}_t$$

and it simply checks whether or not  $\hat{O}_t = \hat{O}_e$  , hence the range of the test is Boolean.

A software test, then contains a point specification for the desired Software.

A software test does not need to be computable. Unfortunately, any automated test, by definition needs to be computable. This also pose a problem for testing in general. A test that might not be computable is a human reporting software has hung or went into infinite loop. This is impossible to do algorithmically, unless we bound the time. This comes under Oracles in computation.

## Branches and Partitions

Given software is written essentially using arithmetic logic and then conditional jump - this being the very definition of Turing Complete languages - that conditional jump ensures that the different inputs takes different code paths. A code path is a path ( even having cycle ) in the control flow graph of the software which starts at the top layer of the directed graph that is the code and ends in the output or bottom later.

Formally we can always create a single input node and output node in any control flow graph.

Treating multiple iterations of the same cycle as a single cycle, we can evidently say given the nodes of the graph is finite, there would be finite ( but incredibly high ) number of flow paths in the graph.

At this point we introduce the notion of equivalence class of input vectors to software. If two inputs  $\hat{I}_x$  and  $\hat{I}_y$  takes the same path  $P$  in the control flow graph, then they are equivalent.

This has immense implication in testing. Because this induces an equivalence partitioning on the input space itself, because all  $\hat{I}_x$  in the same equivalence class can be treated as exactly equivalent, because all of them would follow the exact same code path in the control flow graph.

This effectively means by isolating all equivalence partitions and choosing one input member from each of them we can test the system the most optimal way. For example, if there are  $A, B, C, D$  equivalent classes, then choosing  $\hat{I}_A \in A$  , only one would test the code path for  $A$ , similarly for the rest. So instead of infinite inputs, only 4 inputs would suffice.

This brings the problem, formally to finding the equivalent classes.

That is impossible without the implementation. It is absolutely wrong to perceive that this technique is a specification driven one alone. This is a gray box testing it requires assuming some implementation details. The wikipedia article on this demonstrates this nicely.

But just how many equivalent classes would be possible? This definitely depends on the number of the conditional jumps. It is easy to prove that if there are  $B$  branches, then the bound of the equivalence class is  $O(2^B)$  - a huge number. This also would be very important for a pragmatic discussion later.

The Equivalent classes would be called EQCP from now on because they partition the input set into Equivalent Classes.

## Coupling in Software

Given individual EQCP are nothing but depicting paths in the control flow graph ( CFG ), the coupling said to exists between EQCPs  $E_x$  with path  $P_x$  and  $E_y$  with path  $P_y$  if and only if  $P_x \cap P_y \neq \emptyset$ .

That is, if paths  $P_x, P_y$  has some common edges, then  $E_x, E_y$  are coupled. In fact we can define the amount of coupling using similarity measures now, most easy one would be a Jaccard distance like measure:

$$C(E_x, E_y) = \frac{|P_x \cap P_y|}{|P_x \cup P_y|}$$

This essentially says - "Measure of the coupling between two equivalent classes is the amount of code flow shared between them relative to all code they have".

## Test Driven Development as Equivalent Class Specification

By following the definitions till now, we can now formally define a software system specification in a finite, and correct way. If we can just specify the equivalence classes, then we can just fixed the software at those specification points and the resulting tests precisely, and correctly defines the software behavior. This must be taken as the formal definition of TDD.

Given an abstract (not written) Software  $S_a$ , let's imagine the equivalence classes  $E_x$  such that  $E_x, E_y$  are independent and specify the input and output expected from each equivalence classes.

This system is provably complete and correct, by construction. Every test just ensures all individual EQCP behavior is passed via construction.

## Correctness of TDD

The correctness of TDD for a practical application hinges on the following :

1. Is the specification complete enough ( to take care of all the equivalent classes )?
2. Is the specification non contradictory ?

That it is impossible to get (1,2) done together follows from Godel's Incompleteness theorems, but that is applicable to any specification, not only Software. Thus this argument should not be admissible as failure of TDD in itself.

Now we ignore the notion of contradiction and focus on completeness and stability.

## Completeness of TDD Spec

The business specification should be such that the formal specification of all possible Equivalence classes must be drawn from it. As it is bounded by  $O(2^B)$  - this itself is not remotely possible. To understand how this bound works, a simple program `cat` has more than 60 branches. The equivalent class specification of this program is bounded by  $2^{60}$  and the total electrons in the universe is  $10^{80}$  form comparison.

But this again does not disprove the crux of TDD, it only points to the fact that formal EQCP is a practical pragmatic challenge.

Now an incremental TDD is when we add more specification to the mix of already existing ones. This incremental TDD is what we discuss in the next sections as this is the one which proponents of TDD talks about.

## Analysis of Incremental TDD

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### Development in TDD

Note that the methodology does not specify how to implement the paths of each equivalent classes in the code. Hence evidently there is no way it can ever improve on the "non correct aspect of quality" of software, e.g coupling. In fact if not controlled this would bring in way more coupling than it was required due to application of other principles like DRY. There can be of course infinite way to conform to the "point wise convergence". These are some of the interesting properties of the methodology.

The very best non coupled way to deliver would be no equivalence class share any code path. This would solve the coupling problem, but code would be massively bloated. Any other way would reduce the code but ensure the classes would be coupled tighter.

### Stability of TDD Spec over Iteration

It is at this point we go to the heart of the matter. Suppose, there is already an existing system in place with tests done the right way, at least catching up to 1% or 2% of the equivalence classes. Ideally we would want to have way more coverage, and that will be discussed later.

Is it possible to add more specification w/o rewriting existing equivalent classes?

The answer to this is key to the prospect of TDD.

Formally, Software  $S_r$ , as the equivalent classes  $E_x \in \mathbb{E}_r$ , and now more specification change is happening. The following questions need to be asked:

1. How many of the existing EQCP will not be effected by this?
2. How many new EQCP needs to be added?
3. How many EQCP needs to be removed?

As one can surmise, this is a fixed point iteration on the abstract space of the EQCP itself which we shall formally define later on.

### Loose Coupling - A Life Saver

The answer to all these questions is coupling and coupling alone. If the implementation of those equivalent class was such a way that there was minimal coupling, then possibly less classes would be impacted via this. But this is not a principle of TDD in the first place in any form in any practical application of software development. In fact software principle like DRY would mandate code sharing, and hence there would be some coupling.

### Pent Up Branching

The answer to the question [2] is in isolation if there would be  $K$  branches to implement the delta specification - new feature then, the isolated equivalent classes would be in  $O(2^K)$ , thus, the minimum new classes needed would be bounded by this value.

This chance may impact every possible tests because at most it can impact every equivalence class and at least it adds  $O(2^K)$  classes and hence tests.

## Incremental TDD as a Dynamical System

Hence, in Incremental TDD, this culminates into a lot of those equivalence classes being thrown out, new classes being created - a fixed point iteration on the abstract space of the EQCP itself, which we can formally define as follows:

$$\mathbb{E}_{n+1} = \tau(\mathbb{E}_n, \delta_n)$$

Where at step  $n$ ,  $\mathbb{E}_n$  is the current set of EQCPs, while based on new specification (  $\delta_n$  ) and the  $\mathbb{E}_n$  TDD  $\tau$  produces new set of EQCPs (  $\mathbb{E}_{n+1}$  ) for the next step  $n + 1$ . This is the fixed point iteration of incremental software development from point pair specification or incremental TDD.

It is obvious that the first ever specification was :

$$\mathbb{E}_1 = \tau(\emptyset, \delta_0)$$

This is a fixed point iteration on the state space of EQCP, and this now depicts a dynamical, complex system.

## Stability Space

Let's  $N = |X|$  be the cardinality of the set X. Let us create the stability metric as follows:

Ratio of new EQCP unmodified post application of change :

$$\Sigma_{n+1} = \frac{|\mathbb{E}_n \cap \mathbb{E}_{n+1}|}{|\mathbb{E}_n| \cup |\mathbb{E}_{n+1}|}$$

As one can see  $\Sigma_n \in \mathbb{Q} \cap [0, 1]$  , and as close it would remain to 1, the better stable the system is. Observe the following, if we ensure that no EQCP has any shared code, then the only way to make change is to simply add new code, and thus  $\mathbb{E}_n \subset \mathbb{E}_{n+1}$ , and that gives maximum value of  $\Sigma$ . If this is put to practice, there is a guarantee that  $s_n$  follows a very stable path. A value close to 0 shows the system has been very unstable.

## Guiding Stability

Sans the constraint of "no coupling" e.g. assuming coupling has to be present, one way to avoid unpredictable jumps in the stability , we can device our development strategy such that the  $\Sigma$  does not change drastically. At this point, if there were many alternative way to implemented the  $\delta_n$  change, we may want to chose the alternative which minimizes  $\Delta_{n+1} = |\Sigma_{n+1} - \Sigma_n|$ . If we do, then the system remains stable in the short term. But this is a direct anti theses of "less code change", as it minimizing  $\Delta_{n+1}$  culminate into more code change, because it would inherently try to lose some coupling!

## Chaos in Stability space

We now proceed to demonstrate that the iteration driven by  $\delta_n$  in Stability Space has characteristics of chaotic system.

Given there is no universally agreed definition of chaos - most people would accept the following working definition:

Chaos is aperiodic time-asymptotic behavior in a deterministic system which exhibits sensitive dependence on initial conditions.

These characteristics would now be demonstrated under the assumption that some coupling is present.

1. **Aperiodic time-asymptotic behavior**--this implies the existence of phase-space trajectories which do not settle down to fixed points or periodic orbits. For practical reasons, we insist that these trajectories are not too rare. We also require the trajectories to be *bounded: i.e.*, they should not go off to infinity.

The sequence  $\Sigma_n$  is a bounded by definition. The trajectories are not rare, and it is practically impossible for the sequence to settle down to periodic orbits or converging sequence.

Note that w/o the presence of coupling this sequence converges approximating 1.

2. **Deterministic**--this implies that the equations of motion of the system possess no random inputs. In other words, the irregular behavior of the system arises from non-linear dynamics and not from noisy driving forces.

One can argue that the sequence is driven by  $\delta_n$  - an external input, but it is not. Iterative TDD has this baked in, as part of the system and the processing of it is algorithmic in the formal methodology which we present for formal correctness for the software. In fact we can argue that the sequence  $\delta_n$  can be specified beforehand, and it would make it fully deterministic and it would not impact our analysis.

Lack of coupling makes the system extremely deterministic and convergent.

3. **Sensitive dependence on initial conditions**--this implies that nearby points can be spread further over time while distant points can come close over time - e.g. stretching and folding of the space. In fact it is said to be:

Chaos can be understood as a dynamical process in which microscopic information hidden in the details of a system's state is dug out and expanded to a macroscopically visible scale (*stretching*), while the macroscopic information visible in the current system's state is continuously discarded (*folding*).

This is evident in case of coupling. To micro states of the CFG produces EQCP which produce the sequence  $\Sigma_n$ . Given two nearby points in  $\Sigma_n$  , say  $a, b : |a - b| < \epsilon$  , there is no guarantee that in next iteration how further apart the sequence would go, given even exactly same specification of  $\delta_n$  . Let  $\Sigma(p)$  be the next iteration sequence after starting from  $p$  in  $\Sigma_n$ .

Then the  $|\Sigma(a) - \Sigma(b)| \neq 0$  almost always for all practical purposes and let's define  $\lambda$  as follows:

$$\lambda(a, b) = \frac{|\Sigma(a) - \Sigma(b)|}{|a - b|}$$

A stretch happens when  $\lambda(x, y) > 1$  and a fold happens when  $\lambda(x, y) < 1$ . Evidently, if only folding happens, then every sequence would converge. This is a sheer improbability. In the same way if only stretching happens, then because the sequence is bound, it must converge again to 1, which is the case for non-coupling. Another impossibility.

Therefore, it is much more plausible that a sequence like this would have some intervals where it would stretch and some intervals where it would fold. This is the most likely phenomenon which invariably would generate a sequences diverging and converging in  $\Sigma$  thereby producing the dynamic process that stretches and folds - and thus creating sensitive dependence on initial condition, the hallmark of chaos.

The above points make it very clear that the sequence  $\Sigma$  may show all properties of chaotic dynamics.

Is there a guarantee that chaotic patterns would emerge on each case? Possibly. Fairly regularly. Chaos in software development has been discussed about although not in much formal details like this. If we are very lucky it would not, but it is hard to tell. Only by carefully monitoring the sequences we would be able to claim whether we entered any chaotic sequence or not.

## Practical Behavior of Software Under TDD

### Avoidance

We can try avoiding all of these by either:

1. Making the specification more relaxed - at that point it would specify almost nothing and there would be almost no chaotic behavior because of the state space of EQCP being reduced drastically. This is the placebo, the application of TDD w/o any formalism.
2. Or, we can try to decrease coupling, in which case it would bloat the software by not having shared code path - this would result is unimaginable bloat in the software - given we are looking at very large dimension of EQCP state space.

Evidently, then via [2] incremental TDD, therefore, can only be effectively done in practice when the  $\mathbb{E}_n$  space is extremely small and the context of "Software" is very narrow.

### Domain of Stability for Incremental TDD

What is so wrong about chaos appearing in the phase of "stability" of EQCP ? Well, that means there is a lot of churn in terms of the changes - in the EQCP and that means - a lot of churns in the "pair points specifications" e.g tests which were to "hold the correctness of the software". Evidently this is a huge problem, if in one iteration which was created by a tiny change in specification impacts 50% of the test cases.

The chaotic thesis suggests that not this is only possible, but also highly likely due to the mixing of EQCPs in terms of coupling, and a direct result of code refactoring trying to apply DRY principle.

Hence the formal idea of just fixing input output points can not work generally unless we keep on reducing the scope of the specification. It is guaranteed to work at the Unit Test level by definition. Unfortunately the proponents of TDD want to make it work even at user specification level - where it entirely lose its rigor and has no provable applicability to either improve the quality of the product or the code itself.

The iteration over all existing equivalent classes and new ones makes it a fixed point iteration, and specifically if lucky it may be in the domain of stability, but such zones would be extremely narrow due to the large dimensions in which the system operates. This is well known in the domain of the complex system. It is what the original document wanted to talk about via Hill Climbing, which is not a terrible way of looking at TDD trying to slowly converging into the "Ideal final state of the software" at a step  $n$ . But this document does not want to take that route at all, because it is immaterial for now, for theoretical purpose, whether optimum was reached or not, we are only focused on producing "formally provably correct" Software as that is the superpower of formal TDD when done right as shown in this document.

### Placebo view of Popular "Business Specification based" TDD

The previous issues culminates into less and less specific specifications used in the industry. At that point that they cover so less equivalence classes that TDD would lose all it's effectiveness which is to be found rigorously at the unit test level. Thus we do have a problem, if we specify more and more, the resulting software has high coupling thereby ensuring the iterations are destabilized. If we specify less and less the resulting diluted TDD is just homeopathy, water in the name of medicine but peoples believe making it "work" - a placebo.

Interestingly this is the most popular TDD in the industry because the only way non Unit Testing TDD can be done is by just showing they people are doing TDD, which is not even wrong. There is no effectiveness of TDD for anything that goes of unit test, as was proven. It gives a lot of people something to talk about and mental peace just like Homeopathy sans effectiveness other than placebo.

# Proven Narrow Context Of Applicability

Not all is lost however. As it is proven, if we can go narrower and narrower, to the point when EQCPs stop sharing code with one another, TDD not only becomes formally correct, but also the ONLY methodology known to mankind to develop software. Do these exist? They do, these are the unit tests. We can now formally define scope for formal incremental TDD, which is guaranteed to work - e.g. create formal verifiable correct software as follows:

Unit like tests where implementation of such features do not share any source code, e.g. Independent ( completely decoupled ) - such that in every iteration the decoupling holds true guarantee to hold to verifiable correct behavior.

And it is in this context TDD reigns supreme, not anywhere else. Of course one can try to use a scalpel to dig a canal, it just won't work. Any effort of using the scalpel to create a canal is not only misguided, but futile, and not even wrong.

Do iterative TDD, just ensure all EQCPs are completely decoupled - that is the theory. Now, in practice it is hard to do, even for Unit tests, so a small amount coupling should not really harm the effectiveness via that much - but at that point Chaotic behavior stems in.

Principles like AHA, WET comes in extremely handy in this regard. Even with very less coupling there is no absolute guarantee of formal correctness, but at least we are in the right track more or less unlike placebo.

## Summary

Formal TDD, as presented here, is proved to produce correct software code. The issue with such production is of practical consideration, because inherently it increases coupling when done correctly to ensure we can further add more features to the existing software. If that is not the case, then the addition of more equivalence classes can would would rewrite the entire EQCP mapping by ensuring one must rewrite a very significant amount of tests, and this is also seen in reality. Anything at higher level it would just fail to work.

We also formally represented many informal concepts like "Coupling" and defined formally what "Unit" in unit testing supposed to mean.

TDD is not effective for user level testing, it is proved not to be because it lose out its correctness at that level effectively becoming at best Placebo.

Hence we propose TDD is to be done at the Unit Testing level only, where it works correctly and satisfactorily because of Units should be essentially maximally decoupled. And this should come as no surprise that is precisely what Kent Beck "rediscovered" while talking to other developers - "the only way to do unit like testing in Software".

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