RESEARCH PAPER

Adaptive Boundary: A Novel Testing Algorithm to Equivalent Class Partitioning via Smart Boundary Detection

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Abstract— Software testing is a crucial phase in software development that ensures both functional and non-functional requirements are met [1]. Functional testing focuses on verifying expected behavior, while non-functional testing ensures attributes like usability, efficiency, and reliability [2]. One of the biggest challenges in testing is designing effective test cases [3]. Several methods exist to aid test case generation, and one such widely used technique is Equivalence Class Partitioning [4]. This paper introduces a novel testing algorithm for Equivalence Class Partitioning via Smart Boundary Detection, which provides an efficient way to partition input data. Instead of testing at arbitrary or fixed intervals, the algorithm dynamically divides input ranges based on user-defined boundaries, ensuring comprehensive coverage while reducing redundancy [5]. The process continues iteratively until a predefined threshold is reached. This novel approach enhances software reliability and optimizes test case design by focusing on meaningful partitions rather than exhaustive testing [6]

.**Keywords**: Software testing, functional testing, black-box testing, class partitioning, smart boundary detection.

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1. INTRODUCTION

Software testing plays a critical role in ensuring software quality by detecting errors and verifying expected behavior [7]. The primary goal is to achieve correctness, robustness, and reliability in software systems [8]. Testing helps uncover defects at various stages of development, improving overall quality attributes like performance, usability, and fault tolerance [9].Functional testing confirms that a system fulfills the stated specifications, while non-functional testing examines attributes such as efficiency, protection, dependability, and ease of maintenance [10]. Among various testing strategies, Equivalence Class Partitioning (ECP) is a widely used technique to streamline test case design by dividing input data into partitions where each partition is expected to exhibit similar behavior [11].

Testing Process and Configuration

The software testing process involves two key components [12]:

Software Configuration — The software under test, including its implemented features and functions.

Test Configuration — The set of test cases and input conditions used to validate software behavior.

Test cases are executed, and their results are compared with expected outcomes. If discrepancies occur, errors are identified and reported for debugging [13]. Traditional boundary value analysis (BVA) focuses on testing at specific boundary values, but for large datasets, this method alone may not be sufficient [14].

This paper presents an improved approach to Equivalence Class Partitioning using Smart Boundary Detection, which dynamically identifies key partition points rather than relying on fixed boundary values [15]. This adaptive partitioning technique allows for more precise and efficient test case generation, ensuring that significant test cases are executed while minimizing redundant ones [16].

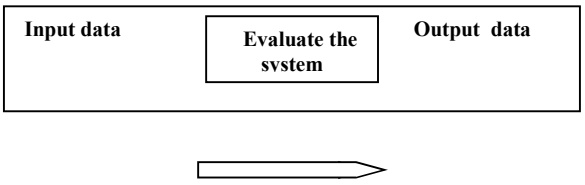

Fig1: Testing: Black box

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2. Performance evaluation of different software modules

An important dimension of software testing is component-level testing, in which separate modules or units are validated prior to integration [18]. Testing coupled components poses additional challenges due to dependencies between modules [19]. An effective software system should aim for high cohesion (strong internal functionality within components) and low coupling (minimal dependency between components) to enhance reliability [20].

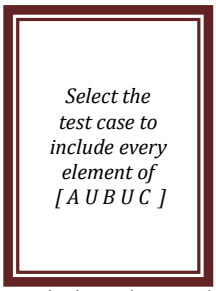
Some widely accepted definitions of component testing include [21]:

IEEE Definition: "Software testing is the process of analyzing a software item to detect differences between existing and required conditions and to evaluate the features of the software item." [22]

Sommerville's Definition: "Component testing is the activity in which individual components are tested to ensure they operate correctly. Each component is tested independently without interference from other system components, identifying gaps and errors." [23]

Broadly, software testing can be categorized into three major types [24]:

Equivalence Class Partitioning —
Categorizes input data into distinct groups to minimize the number of test cases while ensuring broad test coverage [25].
Boundary Value Analysis (BVA) — Focuses on testing at the boundary limits of input ranges [26].
Decision Table Testing — Employs decision tables to evaluate various input conditions along with their corresponding expected outcomes [27].
2.1 Equivalence Class Partitioning Testing
Equivalence Class Partitioning (ECP) is a black-box software



testing technique that optimizes the number of test cases while ensuring effective test coverage [28]. Instead of testing every possible input, ECP groups input values into equivalence classes where each class represents a subset of inputs expected to produce similar results [29]. This minimizes redundancy and ensures that representative test cases are selected to cover multiple scenarios efficiently [30].
Steps in Equivalence Class Partitioning Analysis [31]:
Identify and list all input variables relevant to the system.
Determine equivalence classes for each variable, including valid and invalid partitions.
Define test cases that sufficiently cover all identified equivalence classes.

2.1 Equivalence class partitioning testing:

Equivalence Class Partitioning (ECP) is a black-box software testing technique that optimizes the number of test cases while ensuring effective test coverage. Instead of testing every possible input, ECP groups input values into equivalence classes where each class represents a subset of inputs expected to produce similar results. This minimizes redundancy and ensures that representative test cases are selected to cover multiple scenarios efficiently.

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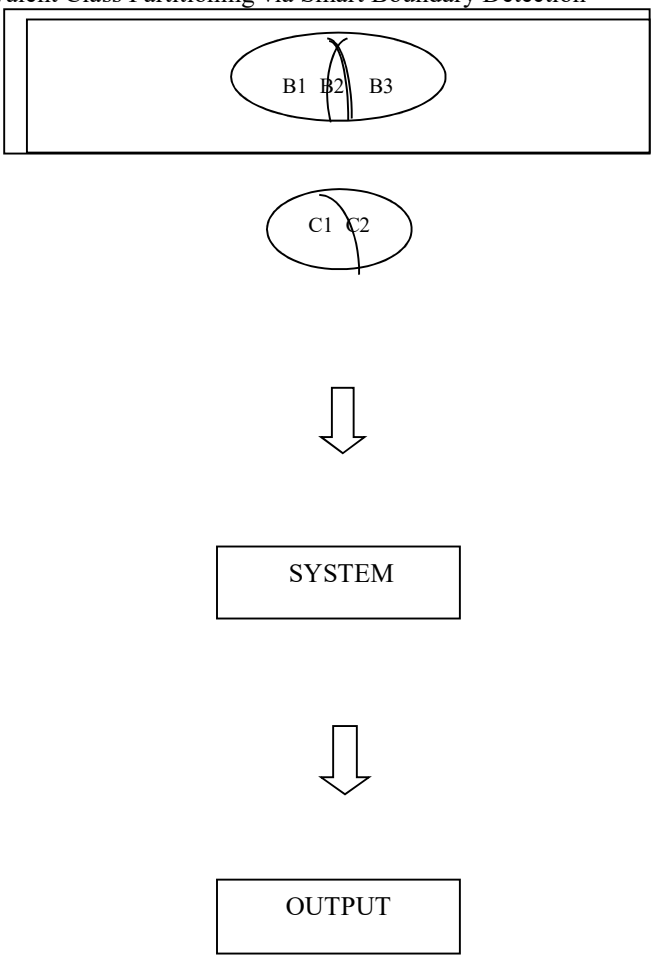


Fig 2. Equivalence class testing

2.2 Boundary Value Analysis:
Boundary Value Analysis (BVA) is a technique that focuses on testing system behavior at boundary conditions of input variables [33]. Since a system often behaves unpredictably at boundaries, it is critical to ensure stability in these regions [34]. BVA selects test cases at the upper, lower, and extreme limits of allowable input values to verify system reliability [35]. Unlike arbitrary test selection, Smart Boundary Detection dynamically identifies critical boundary points, optimizing test efficiency by reducing unnecessary test cases while ensuring crucial boundaries are examined [36].

2.3 Decision Table based Testing

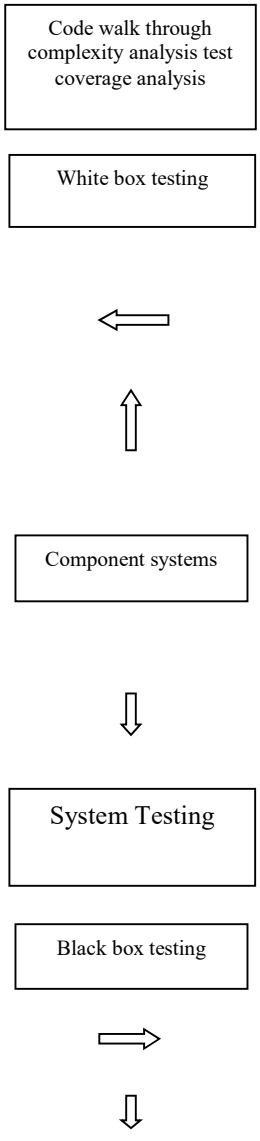
Decision table-based testing is a structured method to represent system behavior under varying input conditions [37]. It is particularly useful for applications where multiple conditions influence system output [38]. A decision table consists of four key components [39]:
Condition Stub — Lists all input conditions relevant to the test.
Condition Entry Stub — Defines all possible unique combinations of these conditions.

Action Stub — Specifies system functionalities expected to execute based on input conditions.

Action Entry Stub — Marks corresponding actions for each input combination.This technique ensures that every decision scenario is accounted for, improving test completeness and functional validation [40].

3. Different challenges in software testing

Despite the advancements in software testing methodologies, several challenges persist [41]. Some of the key difficulties include [42]:Differences in verification and validation approaches between conventional and component-based software testing [43].Component-Based Software Engineering (CBSE) improves quality while reducing cost and time, but challenges arise when integrating third-party components due to varying test standards [44].Early-phase testing is performed by component vendors, whereas users conduct tests later during application development, often leading to inconsistencies in test coverage [45].



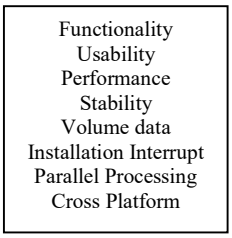


Fig 3. Testing types at a glance

4: Analysis of the related work done

This section highlights previous research in software testing methodologies [47]:

Sequence and State Diagram-Based Testing — Researchers [48] focus on test case generation through system state diagrams.

Component Change Impact Analysis — Studies [49] identify issues arising when a component is modified within an integrated system.

State-Machine-Based Testing — Research [50] suggests using state machines to detect robustness issues and handle invalid inputs effectively.

Path-Oriented Random Testing — Work [15] proposes minimizing redundant test cases by applying path-oriented test selection.

Data Partitioning Strategies — In [16], input data is divided into even and odd classes, applicable specifically to integer-based testing.

String-Based Boundary Value Analysis — Research [17] extends boundary testing to non-numeric variables, optimizing test cases for text-based inputs.

5. Test cases for the proposed work

A critical aspect of software testing is the design of effective test cases [18]. A notable limitation of the Equivalence Partitioning (EP) technique is that it does not inherently focus on boundary values [19]. It groups input data into valid and invalid equivalence classes, and test cases are typically designed to use representative values from the *center* of each class [20].

For example, for an input range of [0, 49], EP would define [21]:

Valid Class: $0 \leq x \leq 49$
Invalid Classes: $x < 0$ and $x > 49$

Test cases might include values like 25 (from the valid class) and -5 and 60 (from the invalid classes). However, this approach risks missing errors that occur specifically at the boundaries (0 and 49). This is why EP is often combined with **Boundary Value Analysis (BVA)**, a technique specifically designed to test the values at the edges of partitions, such as -1, 0, 1, 48, 49, and 50.

A cornerstone of effective software testing is the strategic design of test cases [24]. While Equivalence Partitioning (EP) is a valuable technique for reducing the number of tests, its primary limitation is that it focuses on representative values from the center of a partition and may only test a single boundary per edge [25]. This approach can be insufficient for large or complex input domains, where testing only a few boundaries might leave numerous subtle faults undetected, potentially compromising the software's reliability [26].

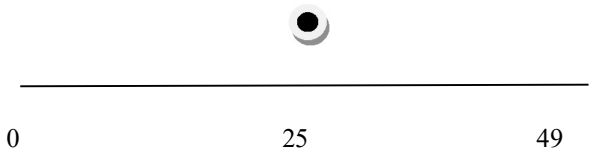
To address this constraint, this paper proposes a novel algorithm that enhances traditional boundary testing [27]. The method empowers the tester to define multiple internal boundaries within a given equivalence partition, effectively creating sub-partitions [28]. This allows for a more granular and rigorous testing process, enabling as many test cases as deemed necessary to achieve a higher confidence level [29].

For example, consider the valid input range [0, 49]. A tester applying this new algorithm could choose to insert one additional internal boundary, thereby creating two sub-partitions [30]. If the tester specifies the new boundary at the value **25**, the original partition is split into [0, 25] and [26, 49]. The resulting test cases would then be designed to verify the boundaries of *each* of these new partitions [31]:

- **For the lower invalid partition and the first sub-partition:**
  - x < 0 (e.g., -1)
  - x = 0 (Lower Boundary of full range)
  - x = 25 (Newly defined internal boundary)
  - x > 25 (e.g., 26)

  For the second sub-partition and the upper invalid partition:
  - x < 26 (e.g., 25)
  - x = 26 (Newly defined internal boundary)
  - x = 49 (Upper Boundary of full range)
  - x > 49 (e.g., 50)

This strategy systematically generates a more comprehensive set of test cases, focusing on both the original and user-defined boundaries to significantly improve fault detection and software reliability.



The flexibility of the proposed algorithm enables a tester to define arbitrary internal boundaries based on risk, intuition, or operational profiles, rather than being constrained by a single large partition [33]. This facilitates a more focused and intensive testing effort on specific segments of the input domain [34].

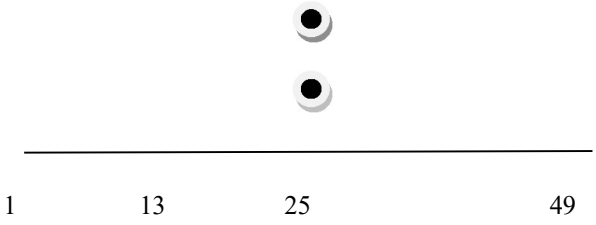
For example, within the original valid range of [1, 49], a tester might suspect that the behavior of the software changes at specific internal points [35]. They could choose to create two boundaries, segmenting the range into three distinct sub-partitions: [1, 13], [14, 25], and [26, 49].

The testing methodology involves applying boundary value analysis to each of these newly created sub-partitions. This means identifying the edges of each segment and designing test cases for values immediately below, at, and immediately above each boundary [36].

The comprehensive set of test cases would be derived from the following critical values:

- **Global Lower Boundary:** x = 0, x = 1
- **First Internal Boundary (13/14):** x = 12, x = 13, x = 14
- **Second Internal Boundary (25/26):** x = 24, x = 25, x = 26
- **Global Upper Boundary:** x = 49, x = 50

This approach generates test cases such as: 0, 1, 12, 13, 14, 24, 25, 26, 49, 50. By creating these sub-partitions, the tester ensures that the boundaries at 13, 14, 25, and 26 are rigorously tested in addition to the global boundaries (1 and 49). This significantly enhances the test coverage and increases the probability of detecting faults that occur at these specific internal points, thereby improving the overall reliability of the software.



6. Proposed Algorithm

1. Start
2. Read domain_size
3. Allocate memory for input_domain of size domain_size
4. If memory allocation fails, display error and stop
5. Read domain_size elements into input_domain
6. Set num_splits = 0
7. Repeat
   - Read temp_pos
   - If temp_pos < 1 or temp_pos >= domain_size, display “Out of bounds” and ask again
   - Check whether temp_pos already exists in partition_points
   - If duplicate, display “Duplicate split position” and ask again
   - Otherwise, store temp_pos in partition_points[num_splits]
   - Increase num_splits by 1
   - Ask user whether to add another split
8. Until user enters n or N
9. Sort partition_points in ascending order
10. Set seg_start = 0
11. For each split position in partition_points

- Set seg_end = split_position - 1
- Print elements from seg_start to seg_end
- Set seg_start = seg_end + 1

12. If seg_start < domain_size, print remaining elements from seg_start to domain_size - 1
13. Free allocated memory
14. Stop

Pseudo Code for Partitioning Input Domain into Segments

```
START
read domain_size
allocate input_domain[domain_size]

if allocation fails
   print "Memory allocation failed"
   stop
end if
read input_domain elements
num_splits = 0
do
   read temp_pos

   if temp_pos < 1 OR temp_pos >= domain_size
      print "Out of bounds"
      continue
   end if
   if temp_pos already exists in partition_points
      print "Duplicate split position"
      continue
   end if
   partition_points[num_splits] = temp_pos
   num_splits++
   read continue_choice
while continue_choice == 'y' OR continue_choice == 'Y'
sort partition_points
seg_start = 0
for each split in partition_points
   print input_domain from seg_start to split - 1
   seg_start = split
end for
print remaining input_domain from seg_start to domain_size
- 1
free input_domain
STOP
```

Out put: For simplicity , the size of an array is in between [0 – 9]. The code is written in C language.

```
Enter Size Of Array==10
Press 1 To Split Array  , Press 2 To Print Splited Array  , Press 3 To Exit
Enter your choice == 1
From Where You Want To Split Array Enter Position ==  4
Enter your choice == 2

 boundary==[ 0  1  2  3  4 ]
boundary==[ 5  6  7  8  9 ]
Enter your choice == 1
From Where You Want To Split Array Enter Position ==  2
Enter your choice == 2

 boundary==[ 0  1  2 ]
 boundary==[ 3  4 ]
boundary==[ 5  6  7  8  9 ]
Enter your choice == 1
From Where You Want To Split Array Enter Position ==  7
Enter your choice == 2

 boundary==[ 0  1  2 ]
 boundary==[ 3  4 ]
 boundary==[ 5  6  7 ]
boundary==[ 8  9 ]
Enter your choice == _
```

Figure 3

7. Step-by-Step Complexity Analysis

Suppose we have N elements in an array taking N=10 and the element of an array is {0,1, 2, 3, 4, 5, 6, 7, 8, 9}. Now suppose the tester wants to split at position 4. Now the result of splitted array will be [0, 1, 2, 3, 4] and [5,6,7,8,9].

Now suppose again the tester wants to split at position 2. Now the result of splitted array will be [0, 1, 2] [3, 4] and [5, 6,7,8,9].

This process continues until we split the last element. So the process can define as:

Case 1: Bisection Strategy (Always splitting segments in half)

- Step 1: N elements in search space
- Step 2: N/2 elements in search space
- Step 3: N/4 elements in search space
- Step 4: 1 element in search space.

The problem is, how many times can we divide N by 2 until we have 1 i.e the last splitted location in an array. Mathematically it can be expressed as:

$1 = N / 2^x$

$2^x = N$

Taking log both side

$\log 2^x = \log N$

$x \log 2 = \log N$

$x = \log N / \log 2$

$x = \log_2 N$ ----------(1)

This means tester can divide $\log_2 N$ times when following bisection strategy.

Case 2: General Case (Splitting at arbitrary positions)

The tester is not limited to bisection; they can split at any position. Therefore:

- Maximum possible splits = **(N - 1)**
- Let the number of splits made = **K** where **$0 \leq K \leq N-1$**

Now every time when we split the boundary, we store the split position in partition_points[] array. After all splits are collected, the sort function is called **once** to arrange the indices of partition_points[] array.

The complexity of sort function:

- To sort the first location of split_pos array compiler will have to compare (K-1) times.
- To sort the second location of split_pos array compiler will have to compare (K-2) times.
- This process continues until the last location is reached.

So this will make a series:

$$(K-1) + (K-2) + (K-3) + \ldots + 3 + 2 + 1$$

This is an Arithmetic progression and the sum of arithmetic progression will be:

$$S = T/2 * (2*a + (T-1)*d)$$

Where T is the total number of elements, a is the first term and d is the common difference.

In the above series:

$a = K-1$, $d = -1$, $T = K$ (number of terms)

$S = K/2 * (2*(K-1) + (K-1)*(-1))$

$= K/2 * (2K - 2 - K + 1)$

$= K/2 * (K - 1)$

$= K*(K-1)/2$

$= K^2/2 - K/2$

$S = O(K^2)$ ----------(2)

General Case Complexity:

Combining the input/output cost $O(N)$ and sorting cost $O(K^2)$:

Total Complexity $= O(N) + O(K^2)$

$= O(N + K^2)$ ----------(3)

Worst Case Complexity:

When the tester splits at every possible position, $K = N-1$:

Total Complexity $= O(N + (N-1)^2)$

$= O(N + N^2 - 2N + 1)$

$= O(N^2)$ ----------(4)

Bisection Strategy Complexity (Special Case):

When tester follows bisection strategy, **$K = \log_2 N$**:

Total Complexity $= O(N + (\log_2 N)^2)$

$= O(N)$ [since N dominates $(\log_2 N)^2$ for large N] ---------(5)

Therefore, the complexity of this algorithm is $O(N + K^2)$ in general, which becomes $O(N^2)$ in the worst case when all possible splits are made. However, if the tester follows the bisection strategy ($K = \log_2 N$), the complexity reduces to $O(N)$.

8. Conclusion:

This paper introduces a novel methodology for enhancing the traditional equivalence class partitioning testing technique. The proposed algorithm, implemented in the C programming language, provides a flexible framework that empowers testers to define multiple partitions within an input domain dynamically. The operational output of the implementation is demonstrated in Figure 3.

A key innovation of this approach is the delegation of control to the tester, who can iteratively refine the number of partitions based on specific testing requirements. This iterative partitioning directly increases the quantity of test inputs generated. Consequently, the test suite's comprehensiveness is significantly improved, leading to a more rigorous validation process. It is posited that this elevation in testing thoroughness directly contributes to a higher degree of software reliability by exposing a greater number of potential faults.

Furthermore, the computational complexity of the algorithm has been formally analyzed and is presented to validate its efficiency and scalability for practical application.

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