

Comparative Analysis of RoBERTa and CodeBERT for Automated Misconfiguration Detection in Dockerfiles

(MIT Thesis Viva Voce Examination)



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ABSTRACT

- This thesis explores automated detection of Dockerfile misconfigurations using transformer-based NLP models.
- A two-stage framework is proposed for binary and rule-specific misconfiguration classification.
- The models are evaluated on a dataset of public Dockerfiles.
- Results show high detection accuracy, with CodeBERT outperforming RoBERTa.

Outline

- Introduction
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- References

Introduction

- Docker is a core technology in modern DevOps for building and deploying applications
- Dockerfiles define container build processes but are complex and under-analyzed
- Misconfigurations in Dockerfiles can cause security vulnerabilities and build failures
- Existing tools detect rule violations but fail to generalize to complex patterns
- This research evaluates transformer-based NLP models to improve Dockerfile misconfiguration detection

This naturally leads to the problem addressed in this thesis.

Problem Statement

- Public Dockerfiles frequently violate best practices and contain security risks
- Many engineers lack deep security expertise when writing Dockerfiles
- Existing tools are rule based and limited to predefined checks which fail to detect unseen patterns
- NLP/AI for Dockerfiles is still underexplored

Problem Statement

traefik:latest [v2.11.34]

- Traefik http router rule



```
traefik.http.routers.${PROJECT}.rule=Host(`api.
${DOMAIN}`) ||
(HostRegexp(`{subdomain:(app)}.${DOMAIN}`
) && PathPrefix(`/api/`))
```

traefik:latest [v3.6.6]

- Traefik http router rule



```
traefik.http.routers.${PROJECT}.rule=Host(`api.
${DOMAIN}`) ||
(HostRegexp(`{subdomain:(app)}.${DOMAIN}`
) && PathPrefix(`/api/`))
```



```
traefik.http.routers.${PROJECT}.rule=Host(`a
pi.${DOMAIN}`) || ((Host(`
app.${DOMAIN}`) && PathPrefix(`/api/`))
```

Objectives

- To design and develop automated detection framework using RoBERTa and CodeBERT
- To evaluate and compare the performance of RoBERTa and CodeBERT for automated misconfiguration detection in Dockerfiles, using metrics such as accuracy, precision, recall, F1-score, and AUC-ROC

Scope and Limitation

- ⚡ **Models compared:** RoBERTa & CodeBERT
- 🔧 **Objective:** Automated detection of Dockerfile misconfigurations
- 📄 **Analysis type:** Static, NLP-based evaluation
- 📊 **Performance metrics:** Accuracy | Precision | Recall | F1-score | AUC-ROC

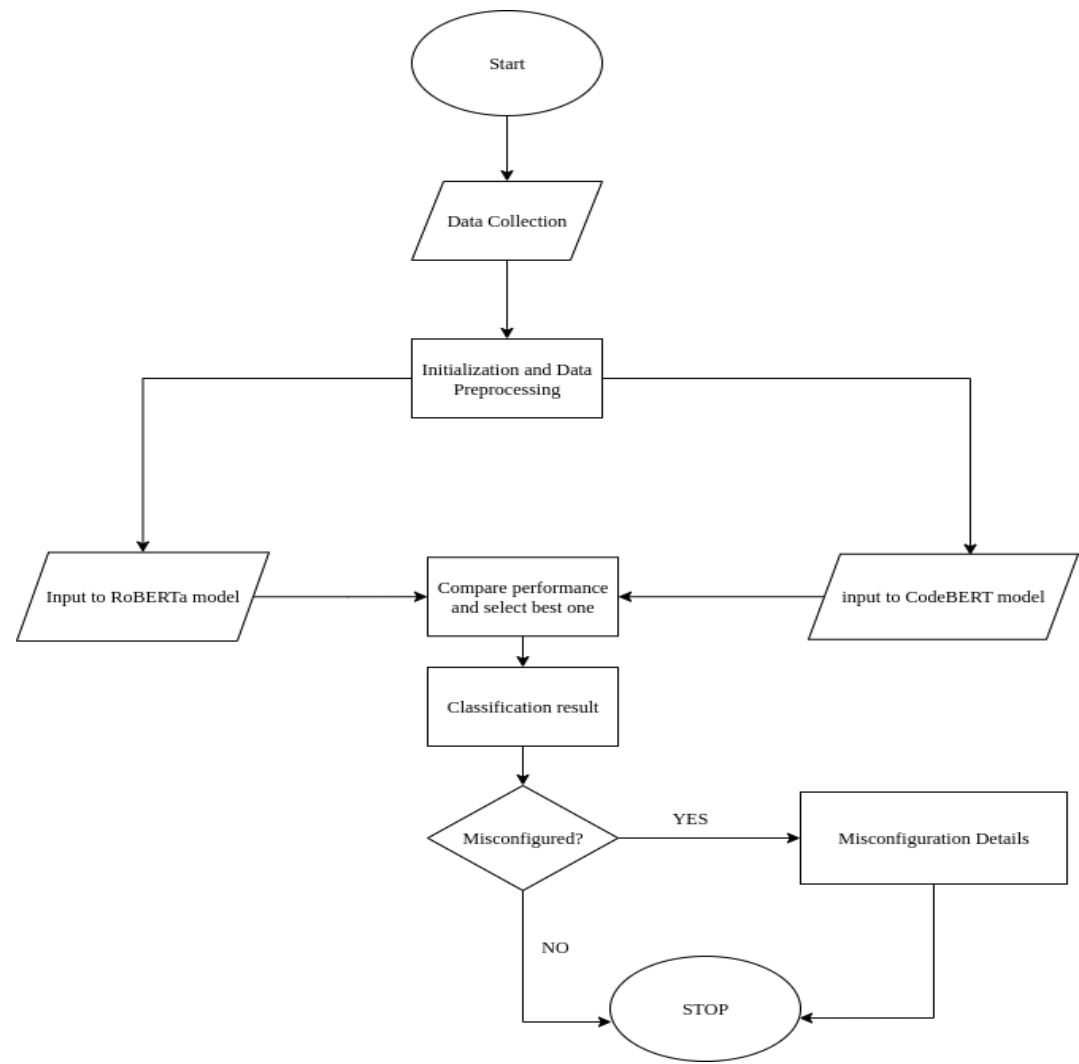
- 🐳 **Scope:** Only Dockerfiles
- 📁 **Dataset:** Publicly available Dockerfiles
- ⚡ **Models:** Only RoBERTa and CodeBERT
- 💻 **Resources:** Limited computational power may affect experiments and tuning

Literature Review

S.No	Study	Dataset	Key findings	Research gap
3	Learning from, DevOps Artifacts	Expert & non-expert Dockerfiles	Non-expert Dockerfiles violate best practices ~6× more	Needs adaptive AI methods for complex misconfigs
4	Shipwright	Faulty Dockerfiles	Automated repair suggestions; Improves build correctness	Focus on build failure, not misconfiguration
5	Dockerfile Flakiness	Flaky Dockerfiles	Characterizes flakiness; Improves repair success	No line-level security detection
6	Dockerfile Linting	Docker Workflows	Ensures consistent quality via linting	No AI/NLP misconfiguration detection
7	Not all Dockerfile Smells are the Same	39,000 Dockerfiles	Experts overlook smells; Validates linting	No AI/NLP detection explored
8	DRIVE: Rule Mining	Dockerfiles	Identifies semantic & syntactic rules	Focus on static rules, not AI/NLP

Methodology

System flow chart



Dataset Description

- Source: Publicly available Dockerfiles from GitHub
- Primary Corpus: Henkel et al. Dockerfile corpus (ICSE 2020)
 - ~178,000 real-world Dockerfiles
- Extended data: Additional Dockerfiles collected via GitHub Search API
- Processing and labels: Dockerfiles parsed line by line; each instruction (e.g., FROM, RUN, COPY) labeled as correct or wrong for training and evaluation of NLP models.
- Dataset Size:
 - 178,800 Dockerfiles
 - ~1.6 million Dockerfile instructions

Data Preprocessing

Model training strategy

- Stage 1: Binary misconfiguration classification
 - Correct vs wrong
- Stage 2: Rule-specific misconfiguration classification
 - Misconfigured instructions with rule id

Data Preprocessing

Data splitting

- Stratified splitting into:
 - Training: 80%
 - Validation: 10%
 - Test: 10%
- Separate strategies for stage 1 and stage 2

Data Preprocessing

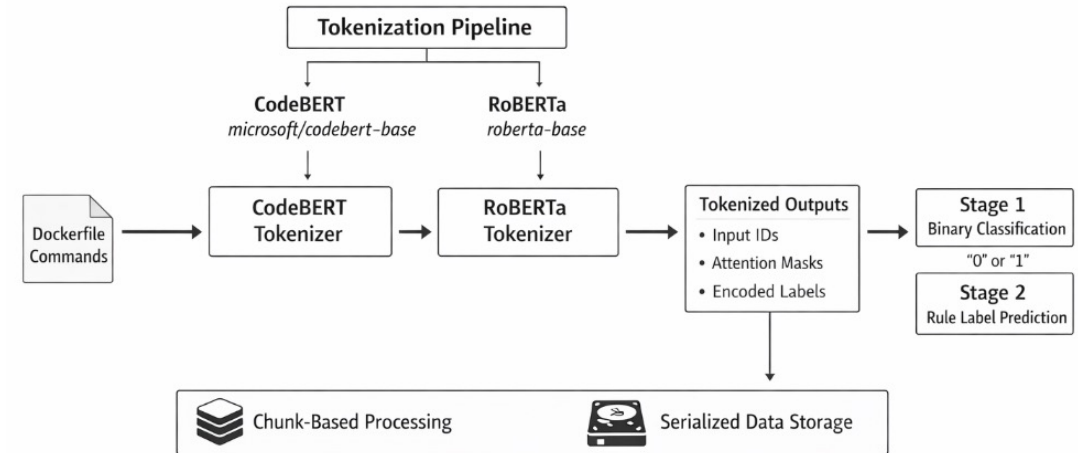
Data splitting

Aspect	Stage 1: Binary classification	Stage 2: Rule-level classification
Task	Correct vs Wrong	Rule-level misconfiguration classification
Initial data	~1.6M instructions	Misconfigured instructions only
Data reduction and balancing method	Downsampled and selected 200K samples per class	Rare rules removed (<200 samples) and capped dominant rules (<=5K)
Final split	80% / 10% / 10% (stratified)	80% / 10% / 10% (rule-stratified)
Motivation	Computational feasibility	Fair multi-class learning and fair computational feasibility

Data Preprocessing

Tokenization and encoding

- Unified subword tokenization applied for both learning stages
- Fixed input length of 256 tokens with truncation and padding
- Training set only label encoding, with pre-tokenized inputs stored for efficient reuse

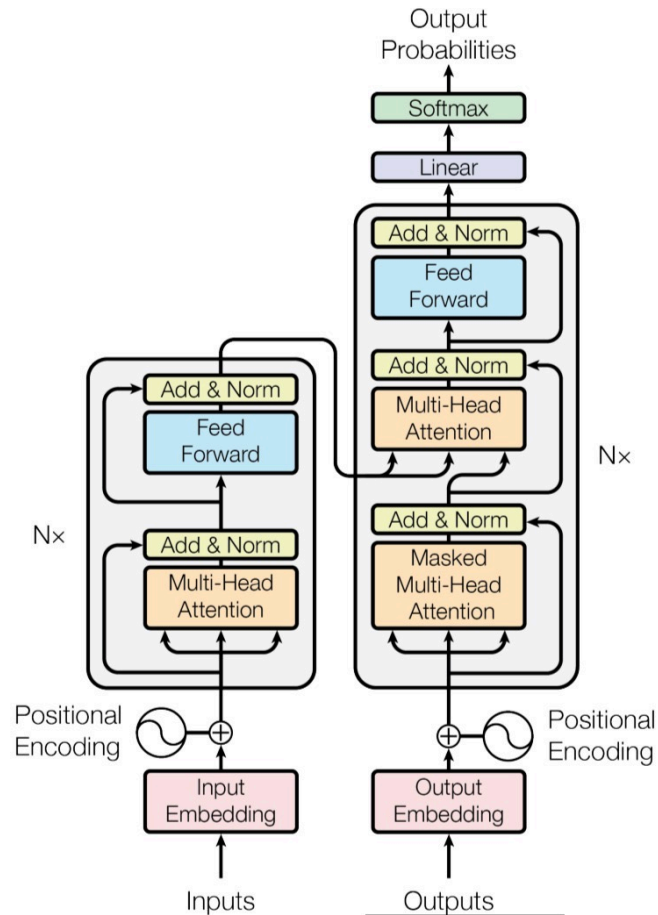


Data Preprocessing

Dataset summary

Aspect	Stage 1: Binary classification	Stage 2: Rule-level classification
Initial dataset	~1.6M instructions	Same dataset
Classes	2 (correct vs wrong)	63 rules
Class balance	2,00,000 per class	Filtered 200+ samples, capped at 5,000 per rule
Total samples used	4,00,000	1,73,297
Training set (80%)	3,20,000	1,38,637
Validation set (10%)	40,000	17,330
Test set (10%)	40,000	17,330
Purpose	Detect misconfiguration	Predict violated rule if misconfigured

Description of Algorithms



- Faster than RNNs/LSTMs: parallel training on large datasets
- Attention mechanism: focuses on most relevant words in context
- Encoder/Decoder: encoder for classification, both for translation
- Self-attention: captures dependencies even across distant words
- Positional encoding: keeps track of word order

Description of Algorithms

RoBERTa and CodeBERT

- Encoder only transformer architecture
- Optimized version of BERT with larger datasets and better training strategies
- Dynamic masking: different tokens are masked in each epoch

Description of algorithms

RoBERTa and CodeBERT

Transformer encoder

- Stack of self-attention layers producing contextualized token representations.
- Input tokens => embedding vectors => processed by encoder layers.

$$\text{Attention}(Q, K, V) = \text{softmax}(QK^T / \sqrt{d_k})V$$

- Where Q, K, V: query, key, value from embeddings and d_k : dimension of key vectors

Classification head

- The [CLS] token embedding from the encoder is passed through a feed-forward layer to produce a probability distribution over class labels, enabling classification of Dockerfiles as correct or misconfigured.

$$y = \text{softmax}(W \cdot h_{CLS} + b)$$

- Where W, b = trainable parameters and y = probability distribution over classes

Implementation Details

Model architecture and input processing

Pretrained models

- RoBERTa-base (text-oriented)
- CodeBERT-base (code-aware)

Tokenization

- Model-specific tokenizers
- Subword encoding
- Maximum sequence length: 256 tokens

Input granularity

- Dockerfile commands processed at line level

Output heads

- Binary classifier (Stage 1)
- Multi-class classifier (Stage 2)

Implementation Details

Training configuration and optimization

Optimizer: AdamW

Learning rate:

- Binary classification: $2 * 10^{-5}$
- Rule classification: $5 * 10^{-5}$

Batch size: 32

Epochs: 3

Training strategy:

- Validation-based loss monitoring
- Gradient accumulation

Loss function:

- Binary classification: Cross-entropy loss
- Rule classification: Multi-class cross-entropy loss

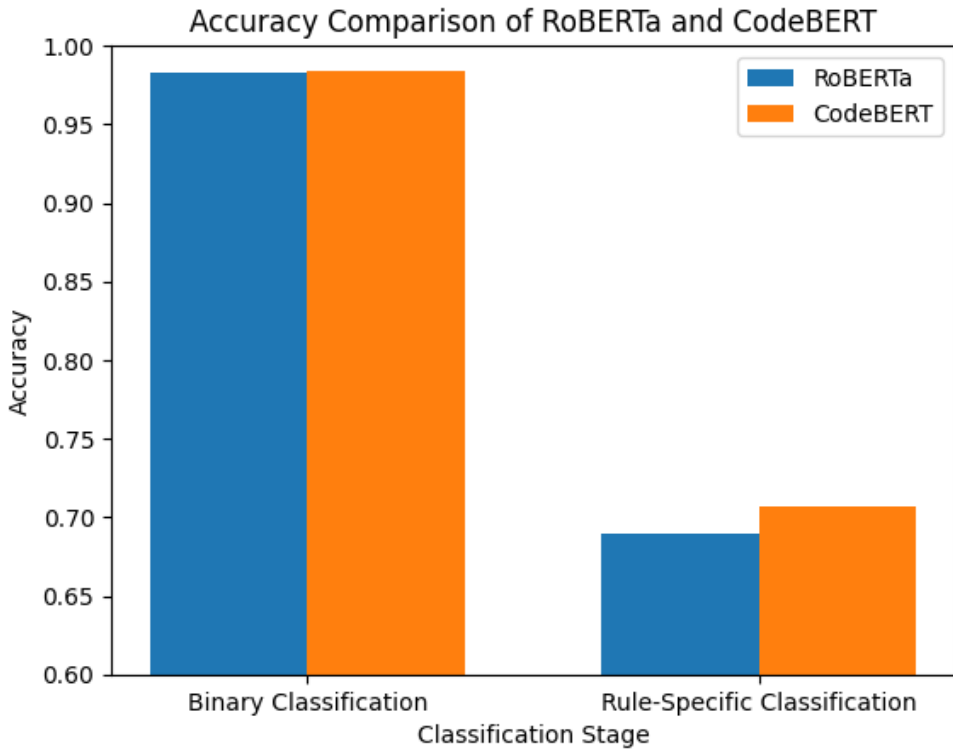
Model persistence:

- Epoch-wise checkpointing for reproducibility

Result Analysis

Accuracy

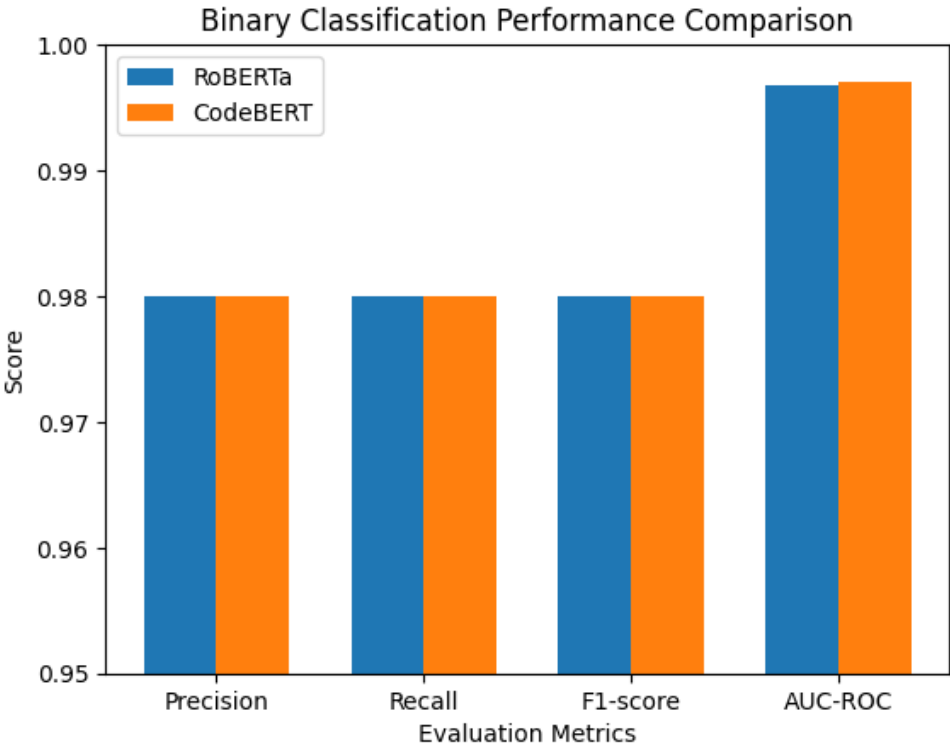
Stages	Models	RoBERTa	CodeBERT	Diff
Binary classification		0.98	0.98	-
Multi class classification		0.7048	0.7070	+0.31%



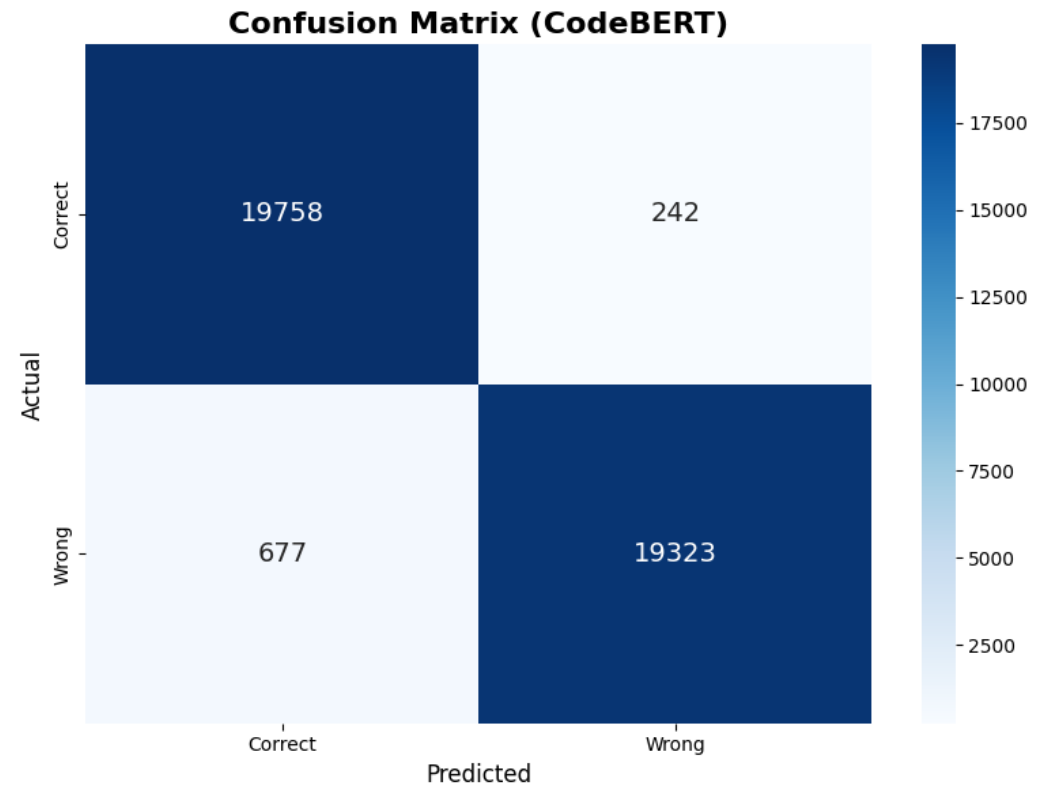
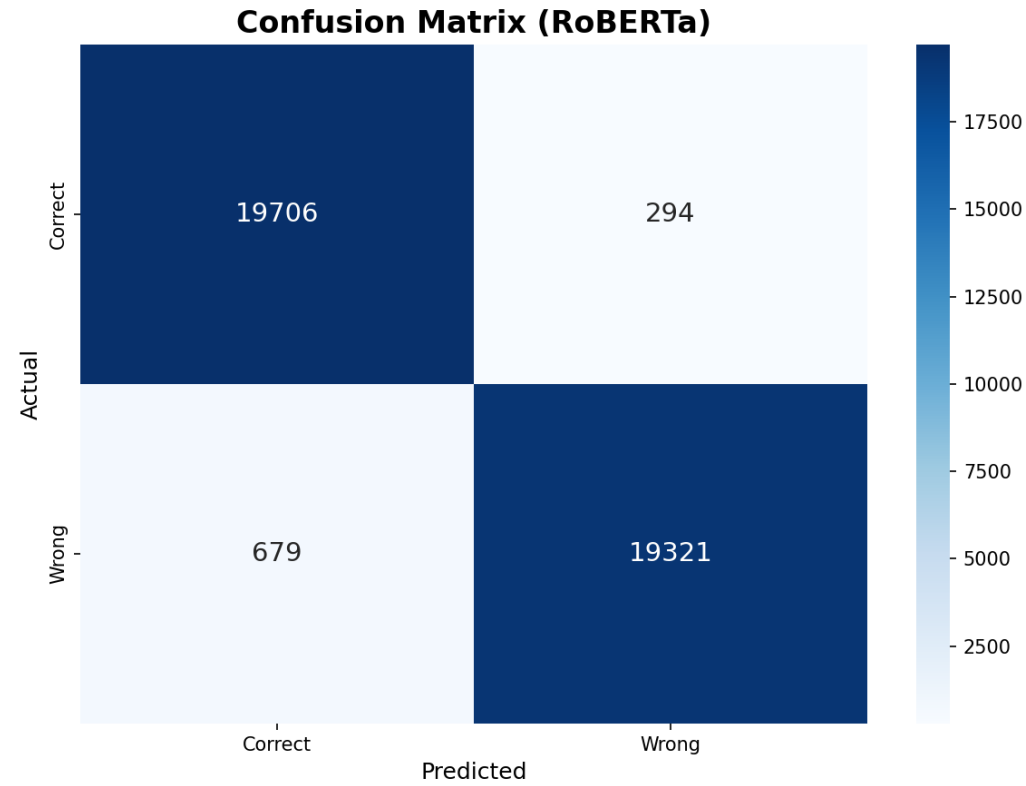
Result Analysis

Binary classification performance

Models	RoBERTa	CodeBERT
Metrics		
Precision	0.98	0.98
Recall	0.98	0.98
F1 score	0.98	0.98
AUC-ROC	0.9968	0.9970



Result Analysis



Result Analysis

Rule(Multi) classification performance (Overall)

<div>Models</div> <div>Metrics</div>	RoBERTa	CodeBERT	Diff
Macro-averaged F1	0.7055	0.7136	+1.15%
Weighted-averaged F1	0.7013	0.7040	+0.38%
Top-1 accuracy	0.7048	0.7070	+0.31%
Top-3 accuracy	0.8901	0.8938	+0.42%

Result Analysis

Per class rule(multi) classification performance

Models	RoBERTa	CodeBERT
Metrics		
Total number of rules	63	63
Average F1-score	0.7055	0.7136 (+1.15%)
Number of rules with $F1 > 0.8$	21	21
Number of rules with $F1 < 0.5$	11	11

Conclusion

- For binary misconfiguration detection, both CodeBERT and RoBERTa achieve excellent and identical performance ($\approx 98\%$ accuracy), demonstrating strong and reliable classification capability.
- In rule-specific misconfiguration classification, CodeBERT outperformed RoBERTa, demonstrating its stronger ability to capture Dockerfile-specific and semantic patterns.
- Although RoBERTa has nearly three times more parameters, its general text pretraining limits its effectiveness for code analysis, while CodeBERT's code centric training enables better rule specific detection.
- Both models are suitable for large-scale binary detection, but CodeBERT is the more effective choice for detailed rule-level analysis due to its code-aware training.

Future Recommendation

- Improve rule-specific classification using larger and more diverse datasets, including data augmentation for rare rules
- Explore ensemble models or hybrid approaches combining transformers with rule-based heuristics
- Integrate the detection framework as a pre-commit Git hook to provide instant feedback on misconfigurations and best practice violations.
- Integrate the proposed models into CI/CD pipelines for real-time misconfiguration detection
- Extend the approach to other IaC technologies such as Terraform, CloudFormation, and Ansible

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Thank you!!!