PACT

Post-route Agentic Checkpoint Tuning for FPGA Timing Closure

Using physical evidence to choose useful ECOs

Huan Lin* Kunlong Li* Lingli Wang Zhiang Wang

College of Integrated Circuits and Micro-Nano Electronics
Fudan University, Shanghai, China

* Equal contribution

A routed DCP is the starting point for ECO

An implemented design can still contain recoverable timing margin.



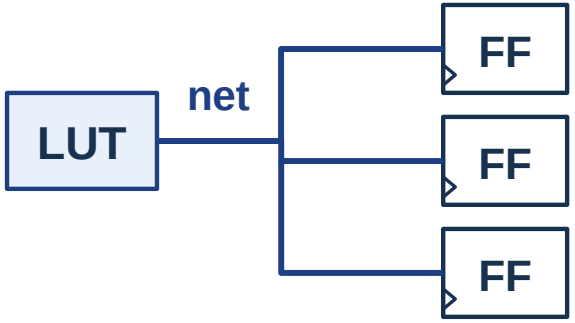
DCP: Design checkpoint, an implemented netlist with placement, routing and timing constraints.
ECO: Engineering Change Order, an edit that preserves the DCP's Functional Equivalence

Problem: Which local repair can improve this particular implementation?

Three physical structures targeted by local ECOs

Start from sampled setup paths in the routed checkpoint

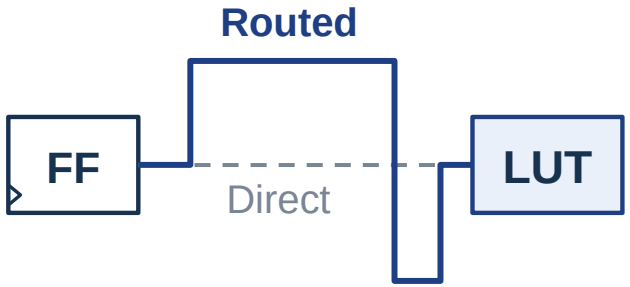
Driver replication



Eligible broadcast net: ≥100 sinks
Rank by path count, then fanout

fanout_opt(net, split_factor)

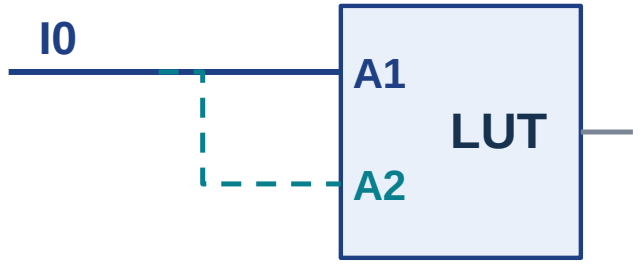
Cell re-placement



Route / direct distance > 2
Auto: cells on the worst 2 paths

cell_replace(auto)

LUT pin swap



Critical LUT input I0–I5
Faster legal physical pin available

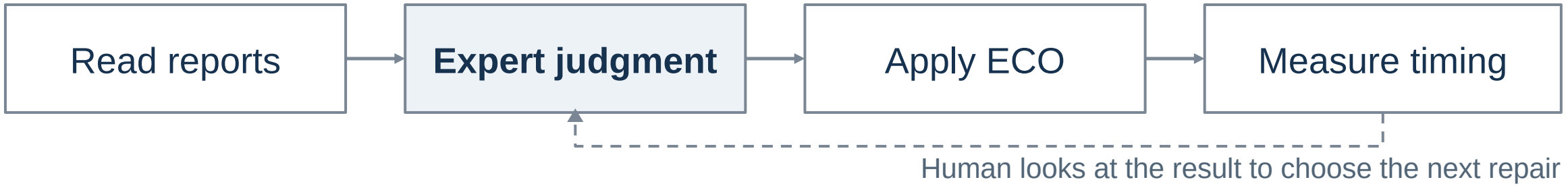
lut_pin_swap(auto)

A named net is passed directly. In auto mode, the skill resolves the legal cell or pin.

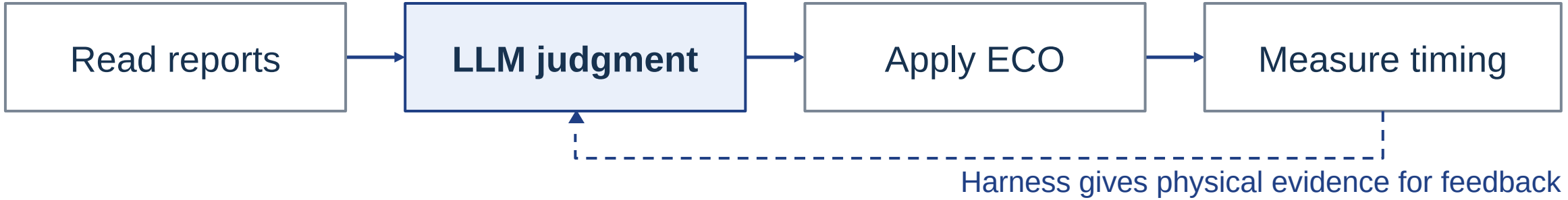
PACT brings LLM reasoning into the ECO decision

The next repair depends on physical evidence and earlier outcomes.

Expert ECO



PACT



The LLM selects ECOs using physical feedback from PACT's tools.

PACT routed FPGA design tools

Two interfaces expose checkpoint evidence and physical editing.

VivadoMCP

Timing-profile extraction

Critical paths, logic / route delay,
slack and high-fanout nets

Implementation control

Routing, physical optimization,
pblocks and clock settings

RapidWrightMCP

Physical-design inspection

Cell / net / pin connectivity,
placement sites and route detours

Object-level ECO routines

Driver replication, cell re-placement,
LUT-cone and input-pin transforms

All 18 actions in PACT v1.0.4

Nine families: five local ECOs, three full-design searches and one control and probing family.

Net, cell and LUT edits

Action	Target or operation
fanout_opt	Copy a driver and split its sinks
force_replicate	Force Vivado driver replication
per_net_unroute	Unroute and repair a named net
critical_net_reroute	Reroute a critical net window
cell_replace	Move a cell beside a route detour
endpoint_bel_move	Move an FF to its paired FF2 BEL
path_local_lut_reflow	Re-place critical-path LUTs
lut_merge	Collapse a compatible LUT cone
lut_pin_swap	Remap a critical LUT input pin

Regions, implementation and control

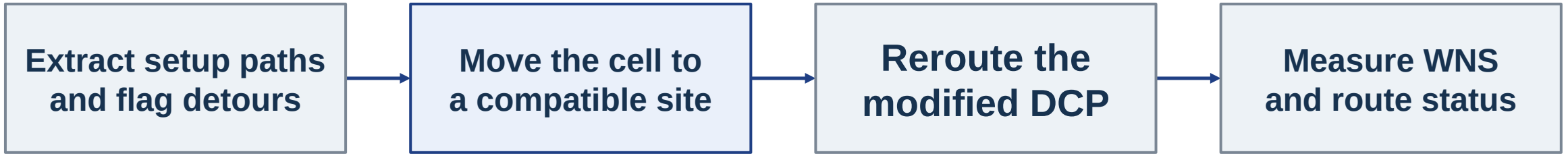
Action	Target or operation
pblock	Constrain cells to a fabric region
pblock_sweep	Compare candidate pblock regions
critical_cluster_anchor	Anchor critical cells in a soft pblock
phys_opt	Apply a physical optimization directive
post_route_cleanup	Try route and physical opt recipes
fresh_place_route	Re-place and reroute the current DCP
clock_tighten	Tighten the clock during search
checkpoint_import	Check a DCP for possible adoption
custom	Call a backend tool in deep analysis

PACT averaged 2.6 effective checkpoint-changing actions per DCP.

How cell re-placement runs a physical trial

Example: cell_replace

target = auto num_paths = 10 detour_threshold = 2.0



Output: candidate DCP, route status, WNS before and after, and an action record.

Promote a clean improvement under the original timing constraints.
Otherwise, keep the accepted DCP and record the trial outcome.

The next ECO starts from the last accepted DCP

At startup, PACT copies the routed input to current_best.dcp.



Acceptance	Restore the original constraints. Check routing, hold and pulse width. For cell_replace, require a WNS gain > 0.5 ps over the accepted DCP.
Next trial	Log the action, target, parameters and ΔWNS for every trial. After a legal trial with too little gain, skip that combination on this DCP and choose another.

Evidence and feedback guide the LLM

Checkpoint evidence

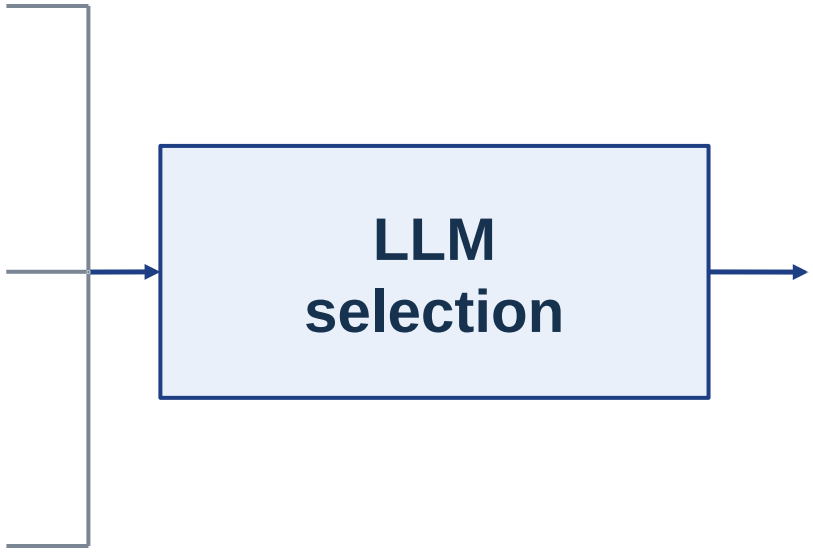
Critical-path samples, net delay, fanout and placement spread

ECO knowledge

Eligible skills, target queues and recipe priorities

Trial feedback

Recent actions, measured ΔWNS, outcomes and remaining budget



Example proposal

cell_replace
target: auto
num_paths: 10
detour_threshold: 2

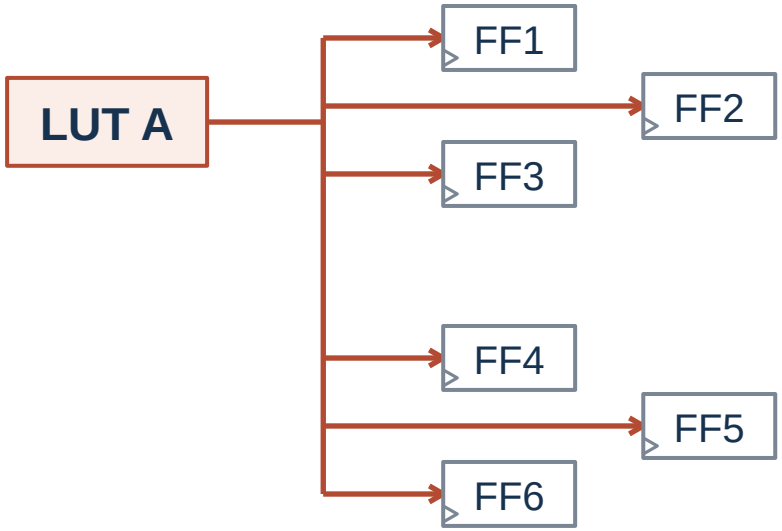
Additional diagnostics

Inspect a path, physical object or tool report.

The LLM selects a permitted repair; auto targeting resolves the physical objects.

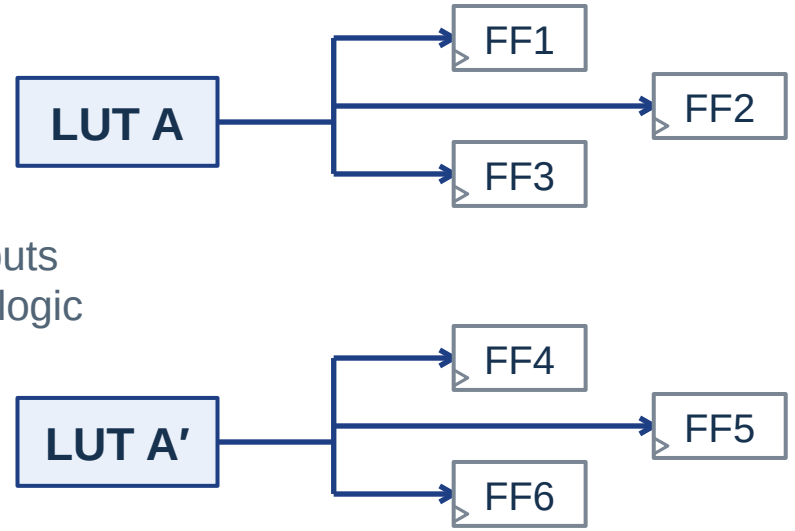
Replication reduces the load on each driver

Before: one LUT driver



One driver reaches both sink groups

After: two equivalent LUTs



With split factor 2, each driver serves one group

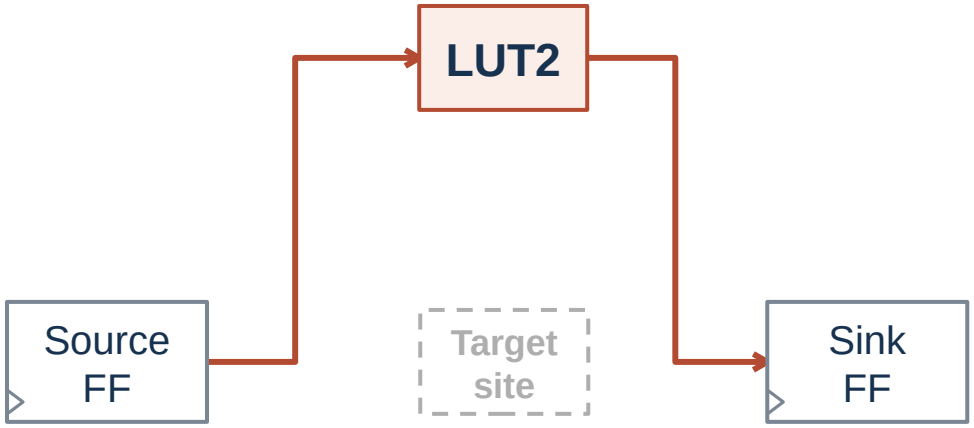
fanout_opt targets a replicable LUT or FF driver on a high-fanout net.

LLM: select the eligible net and split factor. Tools: partition sinks, copy the driver and reroute.

Lower fanout and shorter local routes can reduce delay.

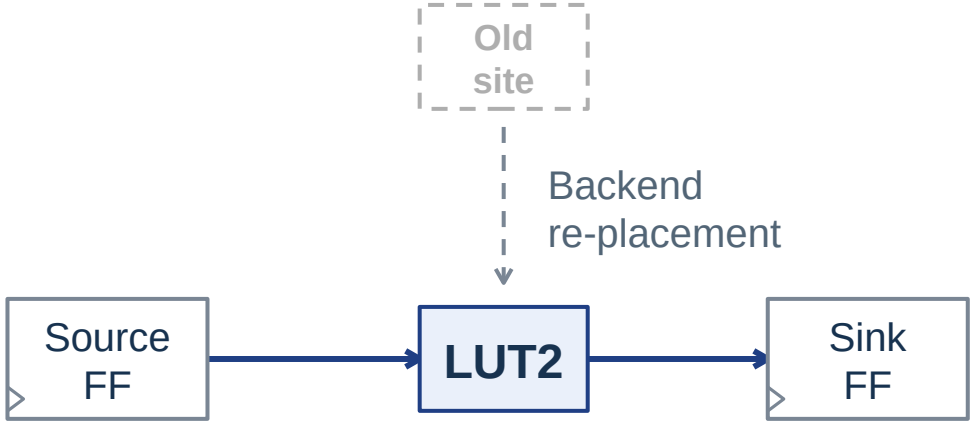
Local re-placement shortens routing connections

Before: distant LUT2



Long connections to the same FFs

After: a nearby legal site



Source and sink positions stay fixed

Auto target: a cell adjacent to a routed detour on a critical path.

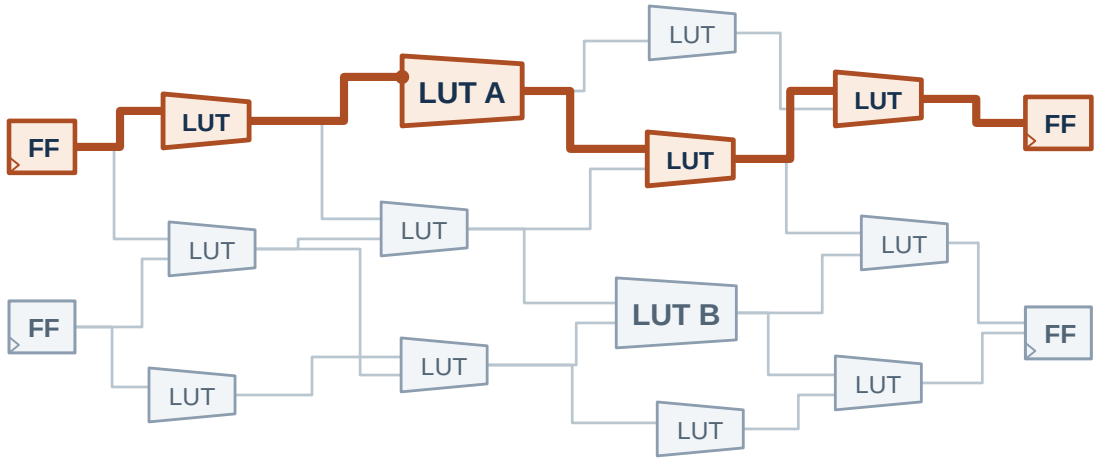
RapidWright searches near the connected-pin centroid for the same BEL type; Vivado reroutes.

Shorter routing detours can reduce critical-path delay.

The critical path shifts from LUT A to LUT B

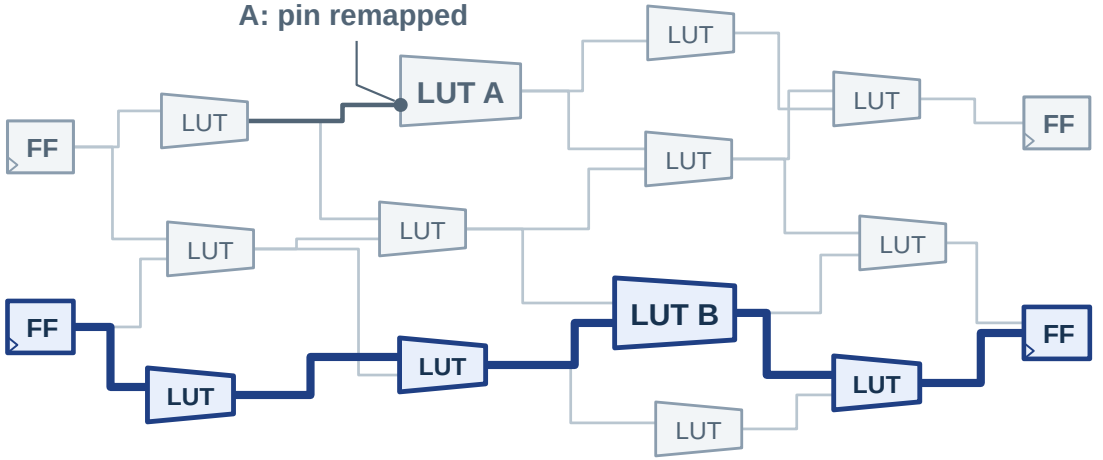
LogicNets local routing schematic. The thick line marks the critical setup path.

Before pass 1: path through LUT A



539.08 MHz WNS: −0.355 ns

After pass 1: path through LUT B



541.13 MHz WNS: −0.348 ns

Pass 2: remap LUT B’s logical I2 to physical input A3.

Reroute and run physical optimization, then measure again.

548.85 MHz

WNS: −0.322 ns

Evaluation setup

35 DCPs

27 development + 8 held-out

xcvu3p-ffvc1517-2-e GPT-5.5

Vivado / RapidWright 2025.1

Ubuntu 22.04 8 cores / 32 GB

Vivado backend

DATuner

Search: up to 12.5 h observed

Structured ECO actions

Scripts

Rule selection

1 h

PACT

LLM-guided ECO

1 h

LLM selection

Codex Agent

Free-form tools

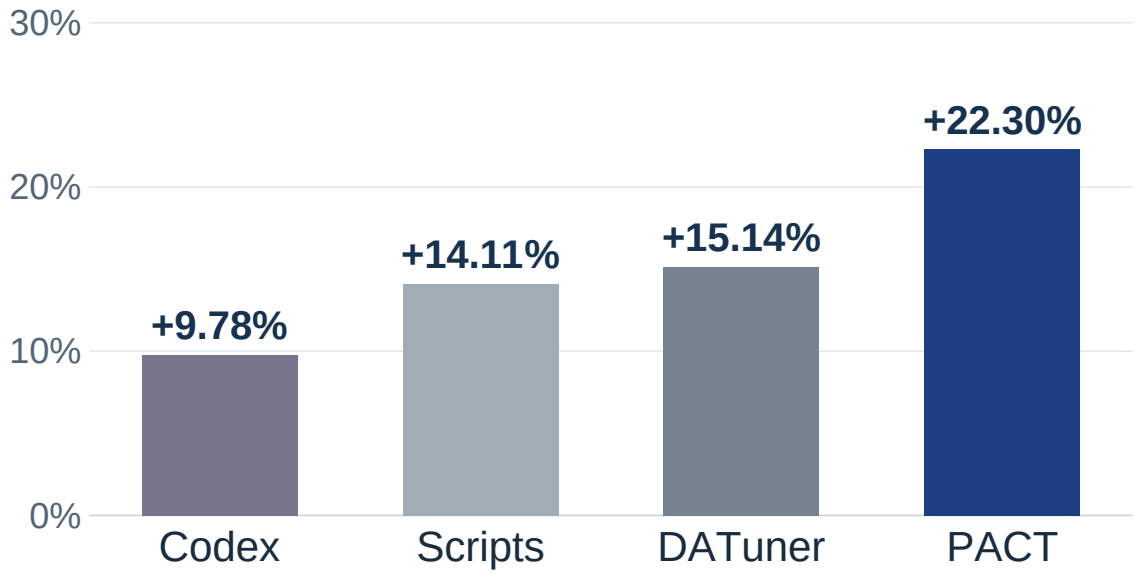
1 h

Metric: geometric-mean Fmax gain over the original DCPs, measured under the original constraints.

PACT improves Fmax by 22.30% across 35 DCPs

Geometric-mean Fmax gain over the original checkpoints

All 35 DCPs



LLM selection versus Scripts

Same ECO actions, validation and 1-hour budget

Design set	Scripts	PACT
Development (27)	+16.78%	**+27.70%**
Held-out (8)	+5.54%	**+5.70%**

Most of the additional gain comes from the development designs.

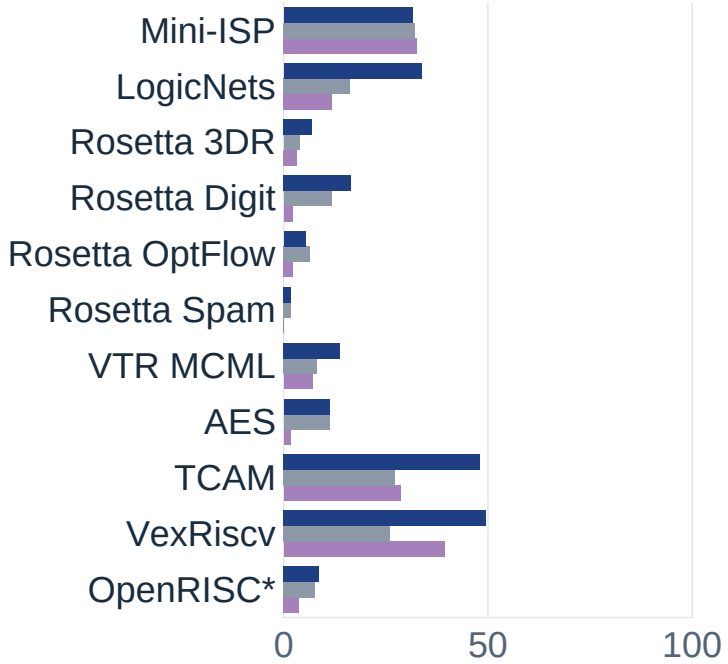
PACT was best or tied-best on 27 of 35 DCPs against DATuner and Codex.

Per-design Fmax gains across all 35 DCPs

Fmax gain over the original DCP (%)

PACT DATuner Codex

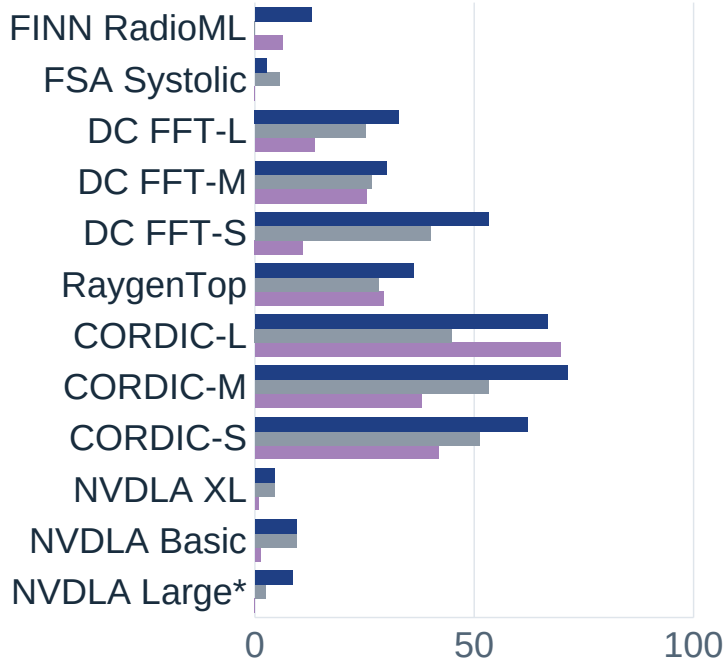
Classic / HLS



Median PACT gain: +13.8%

PACT leads both baselines by >10% on LogicNets, TCAM and VexRiscv.

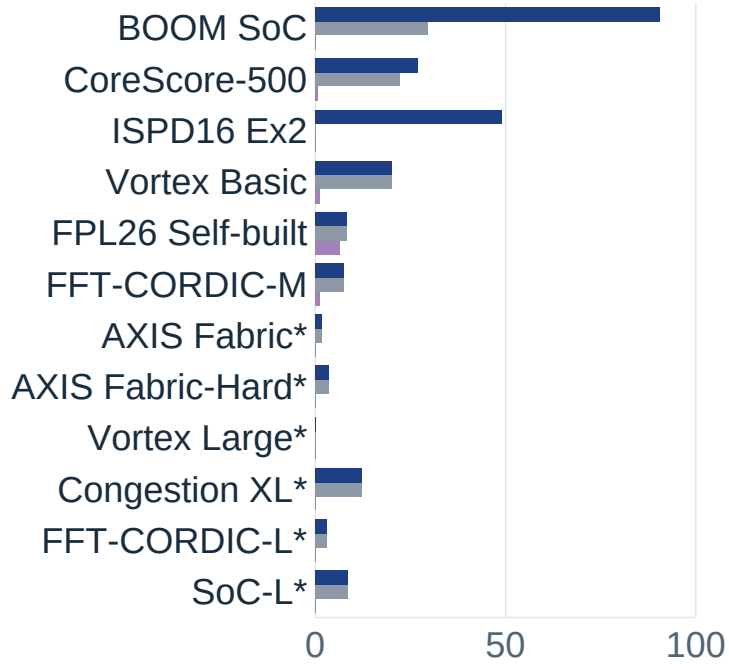
Compute datapaths



Median PACT gain: +31.5%

All three CORDICs gain over 60%. All three NVDLAs gain under 10%.

Systems designs

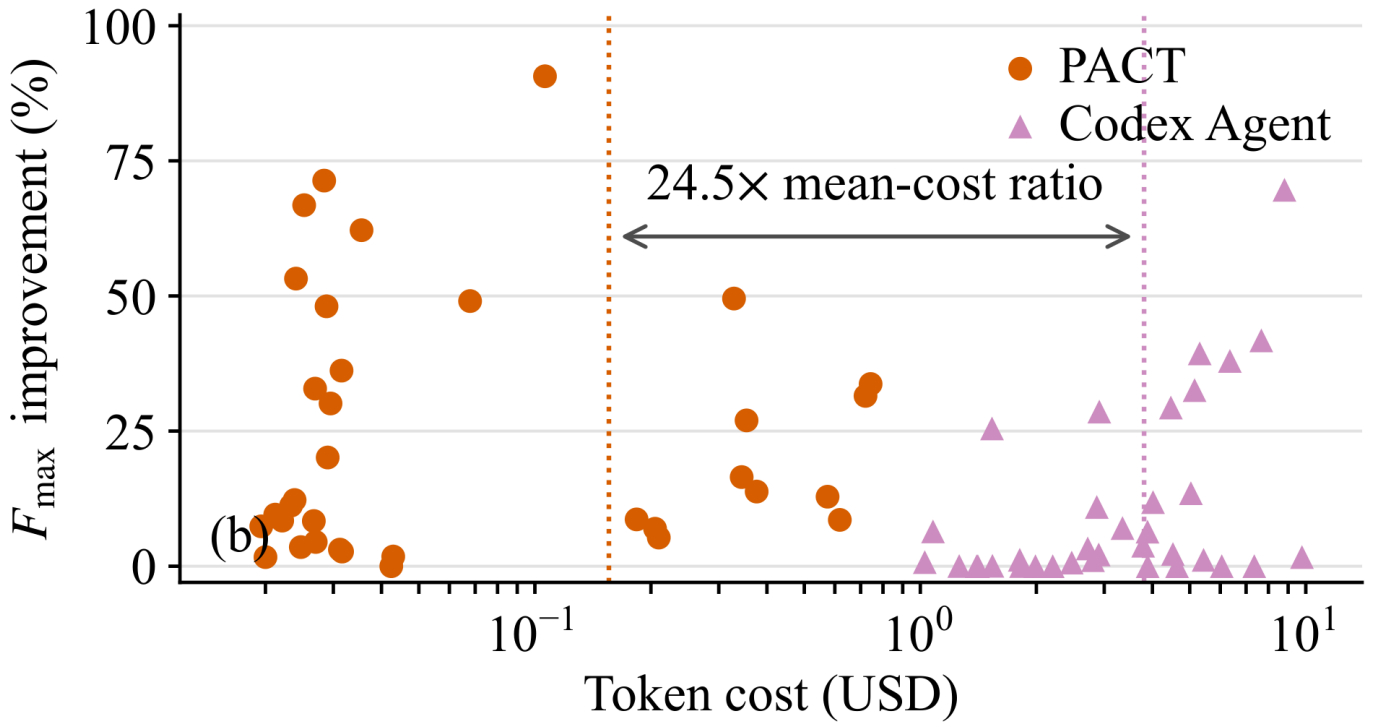


Median PACT gain: +8.4%

Gap to DATuner: <0.1% on 9/12, +61% on BOOM, +49 % on ISPD16.

Lower token cost on all 35 DCPs

PACT and Codex Agent: same 35 DCPs, GPT-5.5 model and 1-hour budget



Cost per DCP

PACT: all below $1, mean $0.16

Codex: all above $1, mean $3.81

BOOM SoC (top orange point)

PACT: +90.7% Fmax for $0.11

Codex: +0.1% Fmax for $1.54

What the LLM chooses

PACT uses timing feedback to pick an ECO. A skill runs and checks the trial. Codex plans individual tool calls. PACT is much **cheaper** than raw Codex.

Mean runtime per DCP: PACT 35.7 min, Codex 25.4 min, DATuner 267.8 min.

Conclusions

Physical feedback guides LLM to choose the next ECO on a routed FPGA checkpoint.

Timing reports identify eligible nets, cells and LUT inputs. The LLM selects a repair, target and parameters. The tools reroute and validate the candidate; outcome information guides the next choice.

Fmax gain

+22.30%

Geometric mean on 35 DCPs.
Scripts achieves +14.11%.

Runtime speedup

6.4×

Paired geometric mean
versus DATuner.

Mean model cost

$0.16

Per DCP with PACT.
Codex costs $3.81 per DCP.

LLM selection helps most on development designs. Held-out gains: PACT +5.70%, Scripts +5.54%.

Paper: arxiv.org/abs/2608.23602

Artifact: github.com/FudanLLMEDA/PACT (v1.0.4)

Thank you for listening

Q&A

Huan Lin · Fudan University

arxiv.org/abs/2608.23602