

Package ‘bioLeak’

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Type Package

Title Leakage-Safe Modeling and Auditing for Genomic and Clinical Data

Version 0.3.6

Description Prevents and detects information leakage in biomedical machine learning.

Provides leakage-resistant split policies (subject-grouped, batch-blocked, study leave-out, time-ordered), guarded preprocessing (train-only imputation, normalization, filtering, feature selection), cross-validated fitting with common learners, permutation-gap auditing, batch and fold association tests, and duplicate detection.

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URL <https://github.com/selcukorkmaz/bioLeak>

BugReports <https://github.com/selcukorkmaz/bioLeak/issues>

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.guard_fit

Fit leakage-safe preprocessing pipeline

Description

Builds and fits a guarded preprocessing pipeline on training data, then constructs a transformer for consistent application to new data.

Usage

```
.guard_fit(  
  X,  
  y = NULL,  
  steps = list(),  
  task = c("binomial", "multiclass", "gaussian", "survival")  
)
```

Arguments

<code>X</code>	matrix/data.frame of predictors (training).
<code>y</code>	Optional outcome for supervised feature selection.
<code>steps</code>	List of configuration options (see Details).
<code>task</code>	"binomial", "multiclass", "gaussian", or "survival".

Details

The pipeline applies, in order:

- Winsorization (optional) to limit outliers.
- Imputation learned on training data only.
- Normalization (z-score or robust).
- Variance/IQR filtering.
- Feature selection (optional; t-test, lasso, PCA).

All statistics are estimated on the training data and re-used for new data.

Value

An object of class "GuardFit" with elements 'transform', 'state', 'p_out', and 'steps'.

See Also

[`predict_guard()`]

Examples

```
x <- data.frame(a = c(1, 2, NA), b = c(3, 4, 5))  
fit <- .guard_fit(x, y = c(1, 2, 3),  
                 steps = list(impute = list(method = "median")),  
                 task = "gaussian")  
fit$transform(x)
```

as_rsampl

Convert LeakSplits to an rsampl resampl set

Description

Convert LeakSplits to an rsampl resampl set

Usage

```
as_rsampl(x, data = NULL, ...)
```

Arguments

x	LeakSplits object created by [make_split_plan()].
data	Optional data.frame used to populate rsampl splits. When NULL, the stored 'coldata' from 'x' is used (if available).
...	Additional arguments passed to methods (unused).

Value

An rsampl rset object compatible with tidymodels workflows. The returned object is a tibble with class rset containing:

splits List-column of rsplit objects, each with analysis (training indices) and assessment (test indices).

id Character column with fold identifiers (e.g., "Fold1").

id2 Character column with repeat identifiers (e.g., "Repeat1") when multiple repeats are present; otherwise absent.

The object also carries attributes for group, batch, study, time (when available from the original LeakSplits), and bioLeak_mode indicating the original splitting mode. This allows the splits to be used with tune::tune_grid(), rsampl::fit_resamples(), and other tidymodels functions.

Examples

```
if (requireNamespace("rsampl", quietly = TRUE)) {
  df <- data.frame(
    subject = rep(1:10, each = 2),
    outcome = rbinom(20, 1, 0.5),
    x1 = rnorm(20),
    x2 = rnorm(20)
  )
  splits <- make_split_plan(df, outcome = "outcome",
                           mode = "subject_grouped", group = "subject", v = 5)
  rset <- as_rsampl(splits, data = df)
}
```

audit_leakage

Audit leakage and confounding

Description

Computes a post-hoc leakage audit for a resampled model fit. The audit (1) runs a permutation-gap test comparing observed cross-validated performance to a label-permutation null (by default refitting when data are available; otherwise using fixed predictions), (2) tests whether fold assignments are associated with batch or study metadata (confounding by design), (3) scans features for unusually strong outcome proxies, and (4) flags duplicate or near-duplicate samples in a reference feature matrix.

The returned [LeakAudit] summarizes these diagnostics. It relies on the stored predictions, splits, and optional metadata; it does not refit models unless 'perm_refit = TRUE' (or 'perm_refit = "auto"' with a valid 'perm_refit_spec'). Results are conditional on the chosen metric and supplied metadata/features and should be interpreted as diagnostics, not proof of leakage or its absence.

Usage

```
audit_leakage(
  fit,
  metric = c("auc", "pr_auc", "accuracy", "macro_f1", "log_loss", "rmse", "cindex"),
  B = 200,
  perm_stratify = FALSE,
  perm_refit = "auto",
  perm_refit_auto_max = 200,
  perm_refit_spec = NULL,
  perm_mode = NULL,
  time_block = c("circular", "stationary"),
  block_len = NULL,
  include_z = TRUE,
  ci_method = c("if", "bootstrap"),
  boot_B = 400,
  parallel = FALSE,
  seed = 1,
  return_perm = TRUE,
  batch_cols = NULL,
  coldata = NULL,
  X_ref = NULL,
  target_scan = TRUE,
  target_scan_multivariate = TRUE,
  target_scan_multivariate_B = 100,
  target_scan_multivariate_components = 10,
  target_scan_multivariate_interactions = TRUE,
  target_threshold = 0.9,
  target_p_adjust = c("none", "BH", "BY", "holm", "bonferroni"),
  target_alpha = 0.05,
```

```

feature_space = c("raw", "rank"),
sim_method = c("cosine", "pearson"),
sim_threshold = 0.995,
nn_k = 50,
max_pairs = 5000,
duplicate_scope = c("train_test", "all"),
learner = NULL,
strict_align = FALSE
)

```

Arguments

<code>fit</code>	A [LeakFit] object from [fit_resample()] containing cross-validated predictions and split metadata. If predictions include learner IDs for multiple models, you must supply <code>'learner'</code> to select one; if learner IDs are absent, the audit uses all predictions and may mix learners.
<code>metric</code>	Character scalar. One of <code>"auc"</code> , <code>"pr_auc"</code> , <code>"accuracy"</code> , <code>"macro_f1"</code> , <code>"log_loss"</code> , <code>"rmse"</code> , or <code>"cindex"</code> . Defaults to <code>"auc"</code> . This controls the observed performance statistic, the permutation null, and the sign of the reported gap.
<code>B</code>	Integer scalar. Number of permutations used to build the null distribution (default 200). Larger values reduce Monte Carlo error but increase runtime.
<code>perm_stratify</code>	Logical scalar or <code>"auto"</code> . If TRUE, permutations are stratified within each fold (factor levels; numeric outcomes are binned into quantiles when enough non-missing values are available). If FALSE, no stratification is used. Defaults to FALSE. Stratification only applies when <code>'coldata'</code> supplies the outcome; otherwise labels are shuffled within each fold.
<code>perm_refit</code>	Logical scalar or <code>"auto"</code> . If FALSE, permutations keep predictions fixed and shuffle labels (association test). If TRUE, each permutation refits the model on permuted outcomes using <code>'perm_refit_spec'</code> . Refit-based permutations are slower but better approximate a full null distribution. The default is <code>"auto"</code> , which refits only when <code>'perm_refit_spec'</code> is provided and <code>'B'</code> is less than or equal to <code>'perm_refit_auto_max'</code> ; otherwise it falls back to fixed-prediction permutations.
<code>perm_refit_auto_max</code>	Integer scalar. Maximum <code>'B'</code> allowed for <code>'perm_refit = "auto"</code> to trigger refitting. Defaults to 200.
<code>perm_refit_spec</code>	List of inputs used when <code>'perm_refit = TRUE'</code> . Required elements: <code>'x'</code> (data used for fitting) and <code>'learner'</code> (parsnip <code>model_spec</code> , workflow, or legacy learner). Optional elements: <code>'outcome'</code> (defaults to <code>'fit@outcome'</code>), <code>'preprocess'</code> , <code>'learner_args'</code> , <code>'custom_learners'</code> , <code>'class_weights'</code> , <code>'positive_class'</code> , and <code>'parallel'</code> . Survival outcomes are not supported for refit-based permutations.
<code>perm_mode</code>	Optional character scalar to override the permutation mode used for restricted shuffles. One of <code>"subject_grouped"</code> , <code>"batch_blocked"</code> , <code>"study_loocv"</code> , or <code>"time_series"</code> . Defaults to the split metadata when available (including <code>rsample</code> -derived modes).

time_block	Character scalar, "circular" or "stationary". Controls block permutation for 'time_series' splits; ignored for other split modes. Default is "circular".
block_len	Integer scalar or NULL. Block length for time-series permutations. NULL selects 'max(5, floor(0.1 * fold_size))'. Larger values preserve more temporal structure and yield a more conservative null.
include_z	Logical scalar. If TRUE (default), include the z-score for the permutation gap when a standard error is available; if FALSE, 'z' is NA.
ci_method	Character scalar, "if" or "bootstrap". Controls how the standard error and confidence interval for the permutation gap are estimated. Default is "if". "if" uses an influence-function estimate when available; "bootstrap" resamples permutation values 'boot_B' times. Failed estimates yield NA.
boot_B	Integer scalar. Number of bootstrap resamples when 'ci_method = "bootstrap"' (default 400). Larger values are more stable but slower.
parallel	Logical scalar. If TRUE and 'future.apply' is available, permutations run in parallel. Results should match sequential execution. Default is FALSE.
seed	Integer scalar. Random seed used for permutations and bootstrap resampling; changing it changes the randomization but not the observed metric. Default is 1.
return_perm	Logical scalar. If TRUE (default), stores the permutation distribution in 'audit@perm_values'. Set FALSE to reduce memory use.
batch_cols	Character vector. Names of 'coldata' columns to test for association with fold assignment. If NULL, defaults to any of "batch", "plate", "center", "site", "study" found in 'coldata'. Changing this controls which batch tests appear in 'batch_assoc'.
coldata	Optional data.frame of sample-level metadata. Rows must align to prediction ids via row names, a 'row_id' column, or row order. Used to build restricted permutations (when the outcome column is present), compute batch associations, and supply outcomes for target scans. If NULL, uses 'fit@splits@info\$coldata' when available. If alignment fails, restricted permutations are disabled with a warning.
X_ref	Optional numeric matrix/data.frame (samples x features). Used for duplicate detection and the target leakage scan. If NULL, uses 'fit@info\$X_ref' when available. Rows must align to sample ids (split order) via row names, a 'row_id' column, or row order; misalignment disables these checks.
target_scan	Logical scalar. If TRUE (default), computes per-feature outcome associations on 'X_ref' and flags proxy features; if FALSE, or if 'X_ref'/outcomes are unavailable, 'target_assoc' is empty. Not available for survival outcomes.
target_scan_multivariate	Logical scalar. If TRUE (default), fits a simple multivariate/interaction model on 'X_ref' using the stored splits and reports a permutation-based score/p-value. This is slower and only implemented for binomial and gaussian tasks.
target_scan_multivariate_B	Integer scalar. Number of permutations for the multivariate scan (default 100). Larger values stabilize the p-value.
target_scan_multivariate_components	Integer scalar. Maximum number of principal components used in the multivariate scan (default 10).

target_scan_multivariate_interactions	Logical scalar. If TRUE (default), adds pairwise interactions among the top components in the multivariate scan.
target_threshold	Numeric scalar in (0,1). Threshold applied to the association score used to flag proxy features. Higher values are stricter. Default is 0.9.
target_p_adjust	Character scalar. Multiple-testing correction method applied to finite 'target_assoc\$p_value' values. One of "none" (default), "BH", "BY", "holm", or "bonferroni". Adds columns 'p_value_adj' and 'flag_fdr' to 'target_assoc'.
target_alpha	Numeric scalar in (0,1). Significance level used for 'flag_fdr' when 'target_p_adjust' != "none". Default is 0.05.
feature_space	Character scalar, "raw" or "rank". If "rank", each row of 'X_ref' is rank-transformed before similarity calculations. This affects duplicate detection only. Default is "raw".
sim_method	Character scalar, "cosine" or "pearson". Similarity metric for duplicate detection. "pearson" row-centers before cosine. Default is "cosine".
sim_threshold	Numeric scalar in (0,1). Similarity cutoff for reporting duplicate pairs (default 0.995). Higher values yield fewer pairs.
nn_k	Integer scalar. For large datasets ('n > 3000') with 'RANN' installed, checks only the nearest 'nn_k' neighbors per row. Larger values increase sensitivity but slow the search. Ignored when full comparisons are used. Default is 50.
max_pairs	Integer scalar. Maximum number of duplicate pairs returned. If more pairs are found, only the most similar are kept. This does not affect permutation results. Default is 5000.
duplicate_scope	Character scalar. One of "train_test" (default) or "all". "train_test" retains only near-duplicate pairs that appear in train vs test in at least one repeat; "all" reports all near-duplicate pairs in 'X_ref' regardless of fold assignment.
learner	Optional character scalar. When predictions include multiple learner IDs, selects the learner to audit. If NULL and multiple learners are present, the function errors; if predictions lack learner IDs, this argument is ignored with a warning. Default is NULL.
strict_align	Logical scalar. If TRUE, errors instead of warning when X_ref or coldata cannot be aligned to predictions by row names or IDs and would otherwise fall back to row-order matching. Default is FALSE for backward compatibility. Set to TRUE in production pipelines to catch silent misalignment.

Details

The 'permutation_gap' slot reports 'metric_obs', 'perm_mean', 'perm_sd', 'gap', 'z', 'p_value', and 'n_perm'. The gap is defined as 'metric_obs - perm_mean' for metrics where higher is better (AUC, PR-AUC, accuracy, macro-F1, C-index) and 'perm_mean - metric_obs' for RMSE/log-loss. By default, 'perm_refit = "auto"' refits models when refit data are available and 'B' is not too large; otherwise it keeps predictions fixed and shuffles labels. Fixed-prediction permutations quantify

prediction-label association rather than a full refit null. Set `'perm_refit = FALSE'` to force fixed predictions, or `'perm_refit = TRUE'` (with `'perm_refit_spec'`) to always refit.

`'batch_assoc'` contains chi-square tests between fold assignment and each `'batch_cols'` variable (`'stat'`, `'df'`, `'pval'`, `'cramer_v'`). `'target_assoc'` reports feature-wise outcome associations on `'X_ref'`; numeric features use AUC (binomial), `'eta_sq'` (multiclass), or correlation (gaussian), while categorical features use Cramer's V (binomial/multiclass) or `'eta_sq'` from a one-way ANOVA (gaussian). The `'score'` column is the scaled effect size used for heuristic flagging (`'flag = score >= target_threshold'`). When `'target_p_adjust != "none"`, finite `'p_value'` entries also receive multiplicity-adjusted `'p_value_adj'` and `'flag_fdr = (p_value_adj <= target_alpha)'`. The univariate target leakage scan can miss multivariate proxies, interaction leakage, or features not included in `'X_ref'`. The multivariate scan (enabled by default for supported tasks) adds a model-based proxy check but still only covers features present in `'X_ref'`.

Duplicate detection compares rows of `'X_ref'` using the chosen `'sim_method'` (cosine on L2-normalized rows, or Pearson via row-centering), optionally after rank transformation (`'feature_space = "rank"'`). By default, `'duplicate_scope = "train_test"'` filters to pairs that appear in train vs test in at least one repeat; set `'duplicate_scope = "all"'` to include within-fold duplicates. The `'duplicates'` slot returns index pairs and similarity values for near-duplicate samples. Only duplicates present in `'X_ref'` can be detected, and checks are skipped if inputs cannot be aligned to splits.

Value

A `LeakAudit` S4 object containing:

`fit` The `LeakFit` object that was audited.

`permutation_gap` One-row data.frame from the permutation-gap test with columns: `metric_obs` (observed cross-validated metric), `perm_mean` (mean of permuted metrics), `perm_sd` (standard deviation), `gap` (observed minus permuted mean, or vice versa for loss metrics), `z` (standardized gap), `p_value` (permutation p-value), and `n_perm` (number of permutations). A large positive gap and small p-value suggest the model captures signal beyond random label assignment.

`perm_values` Numeric vector of length `B` containing the metric value from each permutation. Useful for plotting the null distribution. Empty if `return_perm = FALSE`.

`batch_assoc` Data.frame of chi-square association tests between fold assignment and batch/study metadata, with columns: `variable`, `stat` (chi-square statistic), `df` (degrees of freedom), `pval`, and `cramer_v` (effect size). Small p-values indicate potential confounding by design.

`target_assoc` Data.frame of per-feature outcome associations with columns: `feature`, `type` ("numeric" or "categorical"), `metric` (AUC, correlation, `eta_sq`, or Cramer's V depending on task), `value`, `score` (scaled effect size), `p_value`, `n`, and `flag` (TRUE if `score >= target_threshold`). Flagged features may indicate target leakage.

`duplicates` Data.frame of near-duplicate sample pairs with columns: `i`, `j` (row indices in `X_ref`), `sim` (similarity value), and `cross_fold` (whether the pair spans train vs test). Duplicates across folds can inflate performance.

`trail` List capturing audit parameters and intermediate results for reproducibility, including `metric`, `B`, `seed`, `perm_stratify`, `perm_refit`, and timing info.

`info` List with additional metadata including multivariate scan results when `target_scan_multivariate = TRUE`.

Use `summary()` to print a human-readable report, or access slots directly with `@`.

Examples

```

set.seed(1)
df <- data.frame(
  subject = rep(1:6, each = 2),
  outcome = rbinom(12, 1, 0.5),
  x1 = rnorm(12),
  x2 = rnorm(12)
)

splits <- make_split_plan(df, outcome = "outcome",
  mode = "subject_grouped", group = "subject", v = 3,
  progress = FALSE)

custom <- list(
  glm = list(
    fit = function(x, y, task, weights, ...) {
      stats::glm(y ~ ., data = as.data.frame(x),
        family = stats::binomial(), weights = weights)
    },
    predict = function(object, newdata, task, ...) {
      as.numeric(stats::predict(object,
        newdata = as.data.frame(newdata),
        type = "response"))
    }
  )
)

fit <- fit_resample(df, outcome = "outcome", splits = splits,
  learner = "glm", custom_learners = custom,
  metrics = "auc", refit = FALSE, seed = 1)

audit <- audit_leakage(fit, metric = "auc", B = 10,
  X_ref = df[, c("x1", "x2")])

```

audit_leakage_by_learner

Audit leakage per learner

Description

Runs `audit_leakage()` separately for each learner recorded in a `[LeakFit]` and returns a named list of `[LeakAudit]` objects. Use this when a single fit contains predictions for multiple models and you want model-specific audits. If predictions do not include learner IDs, only a single audit can be run and requesting multiple learners is an error.

Usage

```
audit_leakage_by_learner(
```

```

    fit,
    metric = c("auc", "pr_auc", "accuracy", "macro_f1", "log_loss", "rmse", "cindex"),
    learners = NULL,
    parallel_learners = FALSE,
    mc.cores = NULL,
    ...
  )

```

Arguments

<code>fit</code>	A [LeakFit] object produced by [fit_resample()]. It must contain predictions and split metadata. Learner IDs must be present in predictions to audit multiple models.
<code>metric</code>	Character scalar. One of "auc", "pr_auc", "accuracy", "macro_f1", "log_loss", "rmse", or "cindex". Controls which metric is audited for each learner.
<code>learners</code>	Character vector or NULL. If NULL (default), audits all learners found in predictions. If provided, must match learner IDs stored in the predictions. Supplying more than one learner requires learner IDs.
<code>parallel_learners</code>	Logical scalar. If TRUE, runs per-learner audits in parallel using 'future.apply' (if installed). This changes runtime but not the audit results.
<code>mc.cores</code>	Integer scalar or NULL. Number of workers used when 'parallel_learners = TRUE'. Defaults to the minimum of available cores and the number of learners.
<code>...</code>	Additional named arguments forwarded to [audit_leakage()] for each learner. These control the audit itself. Common options include: 'B' (integer permutations), 'perm_stratify' (logical or "auto"), 'perm_refit' (logical), 'perm_refit_spec' (list), 'time_block' (character), 'block_len' (integer or NULL), 'include_z' (logical), 'ci_method' (character), 'boot_B' (integer), 'parallel' (logical), 'seed' (integer), 'return_perm' (logical), 'batch_cols' (character vector), 'coldata' (data.frame), 'X_ref' (matrix/data.frame), 'target_scan' (logical), 'target_threshold' (numeric), 'target_p_adjust' (character), 'target_alpha' (numeric), 'feature_space' (character), 'sim_method' (character), 'sim_threshold' (numeric), 'nn_k' (integer), 'max_pairs' (integer), and 'duplicate_scope' (character). See [audit_leakage()] for full definitions; changing these values changes each learner's audit.

Value

A named list of `LeakAudit` objects, where each element is keyed by the learner ID (character string). Each `LeakAudit` object contains the same slots as described in `audit_leakage`: `fit`, `permutation_gap`, `perm_values`, `batch_assoc`, `target_assoc`, `duplicates`, `trail`, and `info`. Use `names()` to retrieve learner IDs, and access individual audits with `[[learner_id]]` or `$learner_id`. Each audit reflects the performance and diagnostics for that specific learner's predictions.

Examples

```

set.seed(1)
df <- data.frame(
  subject = rep(1:6, each = 2),

```

```

outcome = factor(rep(c(0, 1), 6)),
x1 = rnorm(12),
x2 = rnorm(12)
)
splits <- make_split_plan(df, outcome = "outcome",
                        mode = "subject_grouped", group = "subject",
                        v = 3, progress = FALSE)
custom <- list(
  glm = list(
    fit = function(x, y, task, weights, ...) {
      stats::glm(y ~ ., data = data.frame(y = y, x),
                family = stats::binomial(), weights = weights)
    },
    predict = function(object, newdata, task, ...) {
      as.numeric(stats::predict(object,
                               newdata = as.data.frame(newdata),
                               type = "response"))
    }
  )
)
custom$glm2 <- custom$glm
fit <- fit_resample(df, outcome = "outcome", splits = splits,
                  learner = c("glm", "glm2"), custom_learners = custom,
                  metrics = "auc", refit = FALSE, seed = 1)
audits <- audit_leakage_by_learner(fit, metric = "auc", B = 10,
                                 perm_stratify = FALSE)
names(audits)

```

audit_report

Render an HTML audit report

Description

Creates an HTML report that summarizes a leakage audit for a resampled model. The report is built from a [LeakAudit] (or created from a [LeakFit]) and presents: cross-validated metric summaries, a label-permutation association test of the chosen performance metric (auto-refit when refit data are available; otherwise fixed predictions), batch or study association tests between metadata and predictions, confounder sensitivity plots, calibration checks for binomial tasks, a target leakage scan based on feature-outcome similarity (with multivariate scan enabled by default for supported tasks), and duplicate detection across training and test folds. The output is a self-contained HTML file with tables and plots for these checks plus the audit parameters used.

Usage

```

audit_report(
  audit,
  output_file = "bioLeak_audit_report.html",
  output_dir = tempdir(),

```

```

  quiet = TRUE,
  open = FALSE,
  ...
)

```

Arguments

audit	A [LeakAudit] object from [audit_leakage()] or a [LeakFit] object from [fit_resample()]. If a [LeakAudit] is supplied, the report uses its stored results verbatim. If a [LeakFit] is supplied, 'audit_report()' first computes a new audit via [audit_leakage(...)]; the fit must contain predictions and split metadata. When multiple learners were fit, pass a 'learner' argument via '...' to select a single model.
output_file	Character scalar. File name for the HTML report. Defaults to '"bioLeak_audit_report.html"'. If a relative name is provided, it is created inside 'output_dir'. Changing this value only changes the file name, not the audit content.
output_dir	Character scalar. Directory path where the report is written. Defaults to [tempdir()]. The directory must exist or be creatable by 'rmarkdown::render()'. Changing this value only changes the output location.
quiet	Logical scalar passed to 'rmarkdown::render()'. Defaults to 'TRUE'. When 'FALSE', knitting output and warnings are printed to the console. This does not change audit results.
open	Logical scalar. Defaults to 'FALSE'. When 'TRUE', opens the generated report in a browser via [utils::browseURL()]. This does not change the report contents.
...	Additional named arguments forwarded to [audit_leakage()] only when 'audit' is a [LeakFit]. These control how the audit is computed and therefore change the report. Typical examples include 'metric' (character), 'B' (integer), 'perm_stratify' (logical), 'batch_cols' (character vector), 'X_ref' (matrix/data.frame), 'sim_method' (character), and 'duplicate_scope' (character). When omitted, [audit_leakage()] defaults are used. Ignored when 'audit' is already a [LeakAudit].

Details

The report does not refit models or reprocess data unless 'perm_refit' triggers refitting ('TRUE' or "auto" with a valid 'perm_refit_spec'); it otherwise inspects the predictions and metadata stored in the input. Results are conditional on the provided splits, selected metric, and any feature matrix supplied to [audit_leakage()]. The univariate target leakage scan can miss multivariate proxies, interaction leakage, or features not included in 'X_ref'; the multivariate scan (enabled by default for supported tasks) adds a model-based check but still only uses features in 'X_ref'. A non-significant result does not prove the absence of leakage, especially with small 'B' or incomplete metadata. Rendering requires the 'rmarkdown' package and 'ggplot2' for plots.

Value

Character string containing the absolute file path to the generated HTML report. The report is a self-contained HTML file that can be opened in any web browser. It includes sections for: cross-validated metric summaries, label-permutation test results (gap, p-value), batch/study association tests, confounder sensitivity analysis, calibration diagnostics (for binomial tasks), target leakage

scan results, and duplicate detection findings. The path can be used with [browseURL](#) to open the report programmatically.

Examples

```
set.seed(1)
df <- data.frame(
  subject = rep(1:6, each = 2),
  outcome = factor(rep(c(0, 1), 6)),
  x1 = rnorm(12),
  x2 = rnorm(12)
)

splits <- make_split_plan(df, outcome = "outcome",
  mode = "subject_grouped", group = "subject",
  v = 3, progress = FALSE)

custom <- list(
  glm = list(
    fit = function(x, y, task, weights, ...) {
      stats::glm(y ~ ., data = data.frame(y = y, x),
        family = stats::binomial(), weights = weights)
    },
    predict = function(object, newdata, task, ...) {
      as.numeric(stats::predict(object,
        newdata = as.data.frame(newdata),
        type = "response"))
    }
  )
)

fit <- fit_resample(df, outcome = "outcome", splits = splits,
  learner = "glm", custom_learners = custom,
  metrics = "auc", refit = FALSE, seed = 1)

audit <- audit_leakage(fit, metric = "auc", B = 5, perm_stratify = FALSE)

if (requireNamespace("rmarkdown", quietly = TRUE) &&
  requireNamespace("ggplot2", quietly = TRUE) &&
  isTRUE(rmarkdown::pandoc_available("1.12.3"))) {
  out_file <- audit_report(audit, output_dir = tempdir(), quiet = TRUE)
  out_file
}
```

Description

Runs a reproducible grid of simulation scenarios across modalities, leakage mechanisms, and split modes using [simulate_leakage_suite()]. This function is designed as a benchmarking harness to quantify detection rates and performance inflation under controlled settings.

Usage

```
benchmark_leakage_suite(
  modalities = c("omics", "imaging_tabular", "ehr_tabular"),
  leakages = c("none", "subject_overlap", "batch_confounded", "peek_norm", "lookahead"),
  modes = c("subject_grouped", "batch_blocked", "time_series"),
  learner = c("glmnet", "ranger"),
  seeds = 1:5,
  B = 200,
  alpha = 0.05,
  parallel = FALSE
)
```

Arguments

modalities	Character vector selecting predefined modality profiles. Supported values: "omics", "imaging_tabular", "ehr_tabular".
leakages	Character vector of leakage mechanisms passed to [simulate_leakage_suite()].
modes	Character vector of split modes passed to [simulate_leakage_suite()].
learner	Character scalar. "glmnet" (default) or "ranger".
seeds	Integer vector of Monte Carlo seeds.
B	Integer scalar. Number of permutations per scenario.
alpha	Numeric scalar in (0, 1). Detection threshold applied to permutation p-values.
parallel	Logical scalar. If TRUE, evaluates scenarios in parallel when 'future.apply' is available.

Value

A data.frame with one row per simulation seed/scenario and columns: 'modality', 'leakage', 'mode', 'seed', observed metric, gap, p-value, and a logical 'detected' flag. A scenario-level summary is attached as 'attr(x, "summary")'.

calibration_summary *Calibration diagnostics for binomial predictions*

Description

Computes reliability curve summaries and calibration metrics for a binomial [LeakFit] using out-of-fold predictions.

Usage

```
calibration_summary(fit, bins = 10, min_bin_n = 5, learner = NULL)
```

Arguments

<code>fit</code>	A [LeakFit] object from [fit_resample()].
<code>bins</code>	Integer number of probability bins for the calibration curve.
<code>min_bin_n</code>	Minimum samples per bin used in plotting; bins smaller than this are retained in the output but can be filtered by the caller.
<code>learner</code>	Optional character scalar. When predictions include multiple learners, selects the learner to summarize.

Value

A list with a 'curve' data.frame and a one-row 'metrics' data.frame containing ECE, MCE, and Brier score.

Examples

```
set.seed(42)
df <- data.frame(
  subject = rep(1:15, each = 2),
  outcome = factor(rep(c(0, 1), 15)),
  x1 = rnorm(30),
  x2 = rnorm(30)
)
splits <- make_split_plan(df, outcome = "outcome",
  mode = "subject_grouped", group = "subject",
  v = 3, progress = FALSE)
custom <- list(
  glm = list(
    fit = function(x, y, task, weights, ...) {
      stats::glm(y ~ ., data = as.data.frame(x),
        family = stats::binomial(), weights = weights)
    },
    predict = function(object, newdata, task, ...) {
      as.numeric(stats::predict(object, newdata = as.data.frame(newdata),
        type = "response"))
    }
  )
)
fit <- fit_resample(df, outcome = "outcome", splits = splits,
  learner = "glm", custom_learners = custom,
  metrics = "auc", refit = FALSE, seed = 1)
cal <- calibration_summary(fit, bins = 5)
cal$metrics
```

check_split_overlap *Check split overlap invariants*

Description

Verifies that a [LeakSplits](#) object satisfies the expected no-overlap constraints for one or more grouping columns. For each fold, the function checks that no group-level value appearing in the test set is also present in the training set.

Usage

```
check_split_overlap(splits, coldata = NULL, cols = NULL, stop_on_fail = TRUE)
```

Arguments

splits	A LeakSplits object from make_split_plan .
coldata	A data.frame of sample metadata. When NULL (default), the function uses splits@info\$coldata if available.
cols	Character vector of column names to check for overlap. When NULL (default), the function infers columns from the split mode (e.g., group for subject_grouped, batch for batch_blocked, both axes for combined).
stop_on_fail	Logical; if TRUE (default), raises an error when any overlap is detected.

Value

A data.frame with one row per fold-by-column combination and columns fold, repeat_id, col, n_overlap (number of overlapping group values), and pass (logical). Invisible. Raises an error if any fold fails and stop_on_fail = TRUE.

confounder_sensitivity *Confounder sensitivity summaries*

Description

Computes performance metrics within confounder strata to surface potential confounding. Requires aligned metadata in 'coldata'.

Usage

```
confounder_sensitivity(
  fit,
  confounders = NULL,
  metric = NULL,
  min_n = 10,
  coldata = NULL,
  numeric_bins = 4,
  learner = NULL,
  strict_align = FALSE
)
```

Arguments

<code>fit</code>	A [LeakFit] object from [fit_resample()].
<code>confounders</code>	Character vector of columns in 'coldata' to evaluate. Defaults to common batch/study identifiers when available.
<code>metric</code>	Metric name to compute within each stratum. Defaults to the first metric used in the fit (or task defaults if unavailable).
<code>min_n</code>	Minimum samples per stratum; smaller strata return NA metrics.
<code>coldata</code>	Optional data.frame of sample metadata. Defaults to 'fit@splits@info\$coldata' when available.
<code>numeric_bins</code>	Integer number of quantile bins for numeric confounders with many unique values.
<code>learner</code>	Optional character scalar. When predictions include multiple learners, selects the learner to summarize.
<code>strict_align</code>	Logical scalar. If TRUE, errors when coldata cannot be aligned by row names or IDs and would fall back to row-order matching. Default is FALSE.

Value

A data.frame with per-confounder, per-level metrics and counts.

Examples

```
set.seed(42)
df <- data.frame(
  subject = rep(1:15, each = 2),
  outcome = factor(rep(c(0, 1), 15)),
  batch = factor(rep(c("A", "B", "C"), 10)),
  x1 = rnorm(30),
  x2 = rnorm(30)
)
splits <- make_split_plan(df, outcome = "outcome",
  mode = "subject_grouped", group = "subject",
  v = 3, progress = FALSE)

custom <- list(
  glm = list(
```

```

fit = function(x, y, task, weights, ...) {
  stats::glm(y ~ ., data = as.data.frame(x),
            family = stats::binomial(), weights = weights)
},
predict = function(object, newdata, task, ...) {
  as.numeric(stats::predict(object, newdata = as.data.frame(newdata),
                           type = "response"))
}
)
)
)
fit <- fit_resample(df, outcome = "outcome", splits = splits,
                  learner = "glm", custom_learners = custom,
                  metrics = "auc", refit = FALSE, seed = 1)
confounder_sensitivity(fit, confounders = "batch", coldata = df)

```

cv_ci

*Confidence intervals for cross-validated metrics***Description**

Computes per-learner confidence intervals for each metric column in a per-fold metrics data.frame. Supports the standard normal/t approach and the Nadeau-Bengio (2003) corrected variance for repeated K-fold CV.

Usage

```

cv_ci(
  metrics_df,
  level = 0.95,
  method = c("normal", "nadeau_bengio"),
  n_train = NULL,
  n_test = NULL
)

```

Arguments

metrics_df	Data.frame with columns fold, learner, and one or more numeric metric columns.
level	Confidence level (default 0.95).
method	One of "normal" or "nadeau_bengio".
n_train	Average number of training samples per fold. Used only when method = "nadeau_bengio". NULL to use fallback variance.
n_test	Average number of test samples per fold. Used only when method = "nadeau_bengio". NULL to use fallback variance.

Value

A data.frame with learner and, for each metric, columns <metric>_mean, <metric>_sd, <metric>_ci_lo, and <metric>_ci_hi.

delta_lsi

*Delta Leakage Sensitivity Index (Delta LSI)***Description**

Compares a naive (potentially leaky) cross-validation pipeline against a guarded (leakage-protected) pipeline and quantifies leakage-induced performance inflation using the Leakage Sensitivity Index (LSI).

Usage

```
delta_lsi(
  fit_leaky,
  fit_guarded,
  metric = "auc",
  exchangeability = c("iid", "by_group", "within_batch", "blocked_time"),
  learner = NULL,
  higher_is_better = NULL,
  block_size = NULL,
  M_boot = 2000L,
  M_flip = 10000L,
  strict = FALSE,
  return_details = FALSE,
  seed = 42L,
  ...
)
```

Arguments

fit_leaky	A LeakFit object from the leaky (unprotected) evaluation pipeline.
fit_guarded	A LeakFit object from the guarded (leakage-protected) evaluation pipeline.
metric	Character. Performance metric to compare. Must appear in <code>fit@metrics</code> of both fits (e.g., "auc", "rmse").
exchangeability	Character. Exchangeability assumption for the sign-flip test. One of "iid" (default), "by_group", "within_batch", "blocked_time". "blocked_time" activates a block sign-flip procedure that flips contiguous groups of repeats together, preserving serial autocorrelation under the null; see <code>block_size</code> . "by_group" and "within_batch" are stored and reported but inference still uses the iid sign-flip procedure (a warning is issued; contributions welcome). "iid" (default) applies the standard independent sign-flip test.
learner	Optional character. Learner name to select from multi-learner fits. If NULL, the first learner found in <code>fit@metrics</code> is used.
higher_is_better	Logical or NULL. Whether a higher value of <code>metric</code> indicates better performance. When NULL (default), auto-detected from the metric name: "rmse",

	"mse", "mae", "log_loss", "brier", "error", "loss", and "deviance" are treated as lower-is-better; all others default to higher-is-better. Setting this correctly ensures that a positive delta_lsi always indicates leakage inflation (the naive pipeline is artificially more optimistic than the guarded one).
block_size	Integer or NULL. Block length for the block sign-flip test, used only when exchangeability = "blocked_time". When NULL (default), the block size is auto-estimated from the first-order autocorrelation of $\{\Delta_r\}$ and capped at $\text{floor}(R/3)$ to ensure at least three independent blocks. A warning is issued when the estimate is used with $R_{\text{eff}} < 20$ because the AR(1) estimate is noisy at small sample sizes. Provide an explicit integer to override auto-estimation.
M_boot	Integer. Number of bootstrap samples for BCa CI (default 2000).
M_flip	Integer. Maximum Monte Carlo samples for sign-flip test when $R_{\text{eff}} > 15$ (default 10000).
strict	Logical. If TRUE, error on insufficient R_{eff} instead of a warning.
return_details	Logical. If TRUE, include the per-repeat Δ_r vector and the original fit objects in the info slot.
seed	Integer. Random seed for bootstrap and sign-flip test.
...	Unused. Reserved for deprecated aliases such as fit_naive.

Details

Method: For each fit, per-fold metric values are extracted from `fit@metrics` (or recomputed from `fit@predictions` if necessary). Fold test-set sizes are used as weights to aggregate fold metrics into per-repeat estimates μ_r . The repeat-level delta $\Delta_r = s \cdot (\mu_r^{\text{naive}} - \mu_r^{\text{guarded}})$ captures leakage-induced performance inflation for each CV repeat, where $s = +1$ for higher-is-better metrics (e.g., AUC) and $s = -1$ for lower-is-better metrics (e.g., RMSE), so that $\Delta_r > 0$ always indicates the naive pipeline is more optimistic than the guarded one.

The **delta_lsi** point estimate is the Huber M-estimator ($k = 1.345$) applied to $\{\Delta_r\}$, which is robust to occasional outlier repeats. **delta_metric** is the arithmetic mean of $\{\Delta_r\}$ for easy interpretation in the original metric's units.

Pairing requires that `fit_leaky` and `fit_guarded` share *identical fold structures* (same test-set membership per fold) in addition to the same number of repeats. When repeat counts match but fold structures differ, a warning is issued and the fits are treated as unpaired.

When $R_{\text{eff}} \geq 5$ (equal, paired repeats), a sign-flip randomization test (Phipson & Smyth, 2010) is performed: under H_0 (no leakage) the sign of each Δ_r is exchangeable. All 2^R sign combinations are enumerated exactly for $R \leq 15$ (no continuity correction); Monte Carlo sampling is used for larger R with the Phipson & Smyth (2010) correction.

BCa bootstrap confidence intervals (Efron, 1987) require $R_{\text{eff}} \geq 10$.

Inference tiers:

"A_full_inference" $R_{\text{eff}} \geq 20$: point + BCa CI + sign-flip p-value; inference_ok = TRUE

"B_signflip_ci" $10 \leq R_{\text{eff}} < 20$: point + sign-flip p-value + BCa CI

"C_signflip" $5 \leq R_{\text{eff}} < 10$: point + sign-flip p-value (no CI)

"D_insufficient" $R_{\text{eff}} < 5$ or unpaired: point estimate only

Value

A `LeakDeltaLSI` object.

See Also

`audit_leakage`, `fit_resample`

fit_resample

Fit and evaluate with leakage guards over predefined splits

Description

Performs cross-validated model training and evaluation using leakage-protected preprocessing (`.guard_fit`) and user-specified learners.

Usage

```
fit_resample(
  x,
  outcome,
  splits,
  preprocess = list(impute = list(method = "median"), normalize = list(method =
    "zscore"), filter = list(var_thresh = 0, iqr_thresh = 0), fs = list(method = "none")),
  learner = c("glmnet", "ranger"),
  learner_args = list(),
  custom_learners = list(),
  metrics = c("auc", "pr_auc", "accuracy"),
  class_weights = NULL,
  positive_class = NULL,
  classification_threshold = 0.5,
  parallel = FALSE,
  refit = TRUE,
  seed = 1,
  split_cols = "auto",
  store_refit_data = TRUE
)
```

Arguments

<code>x</code>	SummarizedExperiment or matrix/data.frame
<code>outcome</code>	outcome column name (if <code>x</code> is SE or data.frame), or a length-2 character vector of time/event column names for survival outcomes.
<code>splits</code>	LeakSplits object from <code>make_split_plan()</code> , or an 'rsample' <code>rset/rsplit</code> .

preprocess	list(impute, normalize, filter=list(...), fs) or a 'recipes::recipe' object. When a recipe is supplied, the guarded preprocessing pipeline is bypassed and the recipe is prepped on training data only. Recipe/workflow leakage guardrails run before fitting; configure policy via options(bioLeak.validation_mode = "warn" "error" "off").
learner	parsnip model_spec (or list of model_spec objects) describing the model(s) to fit, or a 'workflows::workflow'. For legacy use, a character vector of learner names (e.g., "glmnet", "ranger") or custom learner IDs is still supported.
learner_args	list of additional arguments passed to legacy learners (ignored when 'learner' is a parsnip model_spec).
custom_learners	named list of custom learner definitions used only with legacy character learners. Each entry must contain fit and predict functions. The fit function should accept x, y, task, and weights, and return a model object. The predict function should accept object, newdata, and task. For binomial/regression/survival tasks it should return a numeric vector; for multiclass tasks it should return either class labels or a matrix/data.frame of class probabilities.
metrics	named list of metric functions, vector of metric names, or a 'yardstick::metric_set'. When a yardstick metric set (or list of yardstick metric functions) is supplied, metrics are computed using yardstick with the positive class set to the second factor level.
class_weights	optional named numeric vector of weights for binomial or multiclass outcomes
positive_class	optional value indicating the positive class for binomial outcomes. When set, the outcome levels are reordered so that positive_class is treated as the positive class (level 2). If NULL, the second factor level is used.
classification_threshold	Numeric threshold in [0, 1] used to convert binomial probabilities into class predictions for pred_class and accuracy metrics. Ignored for non-binomial tasks.
parallel	logical, use future.apply for multicore execution
refit	logical, if TRUE retrain final model on full data
seed	integer, for reproducibility
split_cols	Optional named list/character vector or "auto" (default) overriding group/batch/study/time column names when 'splits' is an rsample object and its attributes are missing. "auto" falls back to common metadata column names (e.g., 'group', 'subject', 'batch', 'study', 'time'). Supported names are 'group', 'batch', 'study', and 'time'.
store_refit_data	Logical; when TRUE (default), stores the original data and learner configuration inside the fit to enable refit-based permutation tests without manual 'perm_refit_spec' setup.

Details

Preprocessing is fit on the training fold and applied to the test fold, preventing leakage from global imputation, scaling, or feature selection. When a 'recipes::recipe' or 'workflows::workflow' is supplied, the recipe is prepped on the training fold and baked on the test fold. For data.frame or matrix

inputs, columns used to define splits (outcome, group, batch, study, time) are excluded from the predictor matrix. Use `learner_args` to pass model-specific arguments, either as a named list keyed by learner or a single list applied to all learners. For custom learners, `learner_args[[name]]` may be a list with `fit` and `predict` sublists to pass distinct arguments to each stage. For binomial tasks, predictions and metrics assume the positive class is the second factor level; use `positive_class` to control this. Use `classification_threshold` to change the probability cutoff used for class labels and accuracy. Parsnip learners must support probability predictions for binomial metrics (AUC/PR-AUC/accuracy) and multiclass log-loss when requested.

Value

A `LeakFit` S4 object containing:

`splits` The `LeakSplits` object used for resampling.

`metrics` Data.frame of per-fold, per-learner performance metrics with columns `fold`, `learner`, and one column per requested metric.

`metric_summary` Data.frame summarizing metrics across folds for each learner with columns `learner`, and `<metric>_mean` and `<metric>_sd` for each requested metric.

`audit` Data.frame with per-fold audit information including `fold`, `n_train`, `n_test`, `learner`, and `features_final` (number of features after preprocessing).

`predictions` List of data.frames containing out-of-fold predictions with columns `id` (sample identifier), `truth` (true outcome), `pred` (predicted value or probability), `fold`, and `learner`. For classification tasks, includes `pred_class`. For multiclass, includes per-class probability columns.

`preprocess` List of preprocessing state objects from each fold, storing imputation parameters, normalization statistics, and feature selection results.

`learners` List of fitted model objects from each fold.

`outcome` Character string naming the outcome variable.

`task` Character string indicating the task type ("binomial", "multiclass", "gaussian", or "survival").

`feature_names` Character vector of feature names after preprocessing.

`info` List of additional metadata including `hash`, `metrics_used`, `class_weights`, `positive_class`, `sample_ids`, `fold_status`, `refit`, `final_model` (refitted model if `refit = TRUE`), `final_preprocess`, `learner_names`, and `perm_refit_spec` (for permutation-based audits).

Use `summary()` to print a formatted report, or access slots directly with `@`.

Examples

```
set.seed(1)
df <- data.frame(
  subject = rep(1:10, each = 2),
  outcome = rbinom(20, 1, 0.5),
  x1 = rnorm(20),
  x2 = rnorm(20)
)
splits <- make_split_plan(df, outcome = "outcome",
  mode = "subject_grouped", group = "subject", v = 5)
```

```

# glmnet learner (requires glmnet package)
fit <- fit_resample(df, outcome = "outcome", splits = splits,
                  learner = "glmnet", metrics = "auc")

summary(fit)

# Custom learner (logistic regression) - no extra packages needed
custom <- list(
  glm = list(
    fit = function(x, y, task, weights, ...) {
      stats::glm(y ~ ., data = as.data.frame(x),
                family = stats::binomial(), weights = weights)
    },
    predict = function(object, newdata, task, ...) {
      as.numeric(stats::predict(object, newdata = as.data.frame(newdata), type = "response"))
    }
  )
)
fit2 <- fit_resample(df, outcome = "outcome", splits = splits,
                   learner = "glm", custom_learners = custom,
                   metrics = "accuracy")

summary(fit2)

```

guard_to_recipe

Convert guard preprocessing steps to a recipes recipe

Description

Maps bioLeak guard preprocessing steps (impute, normalize, filter, fs) to their closest **recipes** equivalents. Requires the **recipes** package. Steps that have no direct recipe equivalent are skipped with a warning.

Usage

```
guard_to_recipe(steps, formula, training_data)
```

Arguments

steps	A named list of guard preprocessing steps, e.g., <code>list(impute = list(method = "median"), normalize = list(method = "zscore"))</code> .
formula	A model formula (e.g., <code>outcome ~ .</code>).
training_data	A data.frame used to initialize the recipe.

Details

Mapping:

- `impute$method = "median"`: `step_impute_median(all_numeric_predictors())`

- `impute$method = "knn"`: `step_impute_knn(all_predictors(), neighbors = k)`
- `impute$method = "missForest"` or `"mice"`: Warning + `step_impute_median()` fallback
- `normalize$method = "zscore"`: `step_normalize(all_numeric_predictors())`
- `normalize$method = "robust"`: Warning + `step_normalize()` fallback
- `normalize$method = "none"`: No step added
- `filter$var_thresh > 0`: `step_nzv(all_numeric_predictors())`
- `fs$method = "pca"`: `step_pca(all_numeric_predictors(), num_comp = ncomp)`
- `fs$method = "ttest"` or `"lasso"`: Warning, skipped (no recipe equivalent)

Value

A `recipes::recipe` object with the mapped steps added.

impute_guarded

Leakage-safe data imputation via guarded preprocessing

Description

Fits imputation parameters on the training data only, then applies the same guarded transformation to the test data. This function is a thin wrapper around the guarded preprocessing used by `fit_resample()`. Output is the transformed feature matrix used by the guarded pipeline (categorical variables are one-hot encoded).

Usage

```
impute_guarded(
  train,
  test,
  method = c("median", "knn", "missForest", "none"),
  constant_value = 0,
  k = 5,
  seed = 123,
  winsor = TRUE,
  winsor_thresh = 3,
  parallel = FALSE,
  return_outliers = FALSE,
  vars = NULL
)
```

Arguments

<code>train</code>	data frame (training set)
<code>test</code>	data frame (test set)
<code>method</code>	one of "median", "knn", "missForest", or "none"

constant_value	unused; retained for backward compatibility
k	number of neighbors for kNN imputation (if method = "knn")
seed	unused; retained for backward compatibility. Set seed before calling this function if reproducibility is needed.
winsor	logical; apply MAD-based winsorization before imputation
winsor_thresh	numeric; MAD cutoff (default = 3)
parallel	logical; unused (kept for compatibility)
return_outliers	logical; unused (outlier flags not returned)
vars	optional character vector; impute only selected variables

Value

A list (S3 class "LeakImpute") with elements train, test, model, method, summary, and outliers.

See Also

[fit_resample()], [predict_guard()]

Examples

```
train <- data.frame(x = c(1, 2, NA, 4), y = c(NA, 1, 1, 0))
test <- data.frame(x = c(NA, 5), y = c(1, NA))
imp <- impute_guarded(train, test, method = "median", winsor = FALSE)
imp$train
imp$test
```

LeakSplits-class *S4 Classes for bioLeak Pipeline*

Description

These classes capture splits, model fits, and audit diagnostics produced by `make_split_plan()`, `fit_resample()`, and `audit_leakage()`.

Usage

```
## S4 method for signature 'LeakDeltaLSI'
show(object)
```

Arguments

object A [LeakDeltaLSI](#) object.

Value

An S4 object of the respective class.

Slots

mode Splitting mode. One of "subject_grouped", "batch_blocked", "study_loocv", "time_series", or "combined".
indices List of resampling descriptors (train/test indices when available)
info (LeakSplits) Metadata associated with the split plan (mode, coldata, hash, etc.)
splits A ['LeakSplits'] object used for resampling
metrics Model performance metrics per resample
metric_summary Summary of metrics across resamples
audit Audit information per resample
predictions List of prediction objects
preprocess Preprocessing steps used during fitting
learners Learner definitions used in the pipeline
outcome Outcome variable name
task Modeling task name
feature_names Feature names included in the model
info (LeakFit) Metadata about the model fit (sample IDs, timings, provenance, etc.)
fit A ['LeakFit'] object used to generate the audit
permutation_gap Data frame summarising permutation gaps
perm_values Numeric vector of permutation-based scores
batch_assoc Data frame of batch associations
target_assoc Data frame of feature-wise outcome associations
duplicates Data frame detailing duplicate records
trail List capturing audit trail information
info (LeakAudit) Metadata about the audit (mechanism summary, settings, provenance, etc.)
metric Performance metric compared between pipelines
exchangeability Exchangeability assumption used for the sign-flip test
tier Inference tier label based on effective number of repeats
strict Whether strict mode was requested
R_eff Effective number of paired repeats available for inference
delta_lsi Huber-robust point estimate of repeat-level metric difference
delta_lsi_ci BCa 95% CI for delta_lsi (NA when R_eff < 10)
delta_metric Arithmetic mean of repeat-level metric differences
delta_metric_ci BCa 95% CI for delta_metric (NA when R_eff < 10)
p_value Sign-flip randomization test p-value (NA when R_eff < 5 or unpaired)
inference_ok TRUE when tier A (R_eff >= 20, paired, finite p and CI)
folds_naive Per-fold data frame for the naive pipeline
folds_guarded Per-fold data frame for the guarded pipeline
repeats_naive Per-repeat aggregate data frame for the naive pipeline
repeats_guarded Per-repeat aggregate data frame for the guarded pipeline
info (LeakDeltaLSI) Metadata including R_naive, R_guarded, paired status, and block details

See Also

[make_split_plan()], [fit_resample()], [audit_leakage()]

[fit_resample()]

[audit_leakage()], [audit_report()]

[delta_lsi()]

make_split_plan	<i>Create leakage-resistant splits</i>
-----------------	----------------------------------------

Description

Generates leakage-safe cross-validation splits for common biomedical setups: subject-grouped, batch-blocked, study leave-one-out, and time-series rolling-origin. Supports repeats, optional stratification, nested inner CV, and optional prediction horizon/purge/embargo gaps for time series. Note that splits store explicit indices, which can be memory-intensive for large n and many repeats.

Usage

```
make_split_plan(  
  x,  
  outcome = NULL,  
  mode = c("subject_grouped", "batch_blocked", "study_loocv", "time_series", "combined"),  
  group = NULL,  
  batch = NULL,  
  study = NULL,  
  time = NULL,  
  primary_axis = NULL,  
  secondary_axis = NULL,  
  constraints = NULL,  
  v = 5,  
  repeats = 1,  
  stratify = FALSE,  
  nested = FALSE,  
  seed = 1,  
  horizon = 0,  
  purge = 0,  
  embargo = 0,  
  progress = TRUE,  
  compact = FALSE,  
  strict = TRUE  
)
```

Arguments

x	SummarizedExperiment or data.frame/matrix (samples x features). If SummarizedExperiment, metadata are taken from colData(x). If data.frame, metadata are taken from x (columns referenced by group, batch, study, time, outcome).
outcome	character, outcome column name (used for stratification).
mode	one of "subject_grouped", "batch_blocked", "study_loocv", "time_series", "combined".
group	subject/group id column (for subject_grouped). Required when mode is 'subject_grouped'; use 'group = "row_id"' to explicitly request sample-wise CV.
batch	batch/plate/center column (for batch_blocked).
study	study id column (for study_loocv).
time	time column (numeric or POSIXct) for time_series.
primary_axis	List with elements type (one of "subject", "batch", "study") and col (column name). Used only when mode = "combined" to define the primary grouping axis. Deprecated in favor of constraints; still supported for backward compatibility.
secondary_axis	List with elements type and col. Used only when mode = "combined" to define the secondary constraint axis. Training sets exclude samples whose secondary-axis levels appear in the test set. Deprecated in favor of constraints; still supported for backward compatibility.
constraints	A list of constraint specifications for mode = "combined". Each element is a list with type (one of "subject", "batch", "study") and col (column name). The first element defines the primary grouping axis (fold driver); subsequent elements define exclusion constraints (training samples sharing constraint-axis levels with the test set are removed). Requires at least 2 elements. Cannot be used together with primary_axis/secondary_axis.
v	integer, number of folds (k) or rolling partitions.
repeats	integer, number of repeats (>=1) for non-LOOCV modes.
stratify	logical, keep outcome proportions similar across folds. For grouped modes, stratification is applied at the group level (by majority class per group) if outcome is provided; otherwise ignored.
nested	logical, whether to attach inner CV splits (per outer fold) using the same mode on the outer training set (with v folds, 1 repeat).
seed	integer seed.
horizon	numeric (>=0), minimal time gap for time_series so that the training set only contains samples with time < min(test_time) when horizon = 0, and time <= min(test_time) - horizon otherwise.
purge	numeric (>=0), additional gap removed immediately before each time-series test block.
embargo	numeric (>=0), additional exclusion window anchored at the end of each time-series test block. Training rows with time > max(test_time) - embargo are removed.
progress	logical, print progress for large jobs.

compact	logical; store fold assignments instead of explicit train/test indices to reduce memory usage for large datasets. Not supported when nested = TRUE.
strict	logical; deprecated and ignored. 'subject_grouped' always requires a non-NULL 'group'.

Value

A `LeakSplits` S4 object containing:

- `mode` Character string indicating the splitting mode ("subject_grouped", "batch_blocked", "study_loocv", or "time_series").
- `indices` List of fold descriptors, each containing `train` (integer vector of training indices), `test` (integer vector of test indices), `fold` (fold number), and `repeat_id` (repeat identifier). When `compact = TRUE`, indices are stored as fold assignments instead.
- `info` List of metadata including `outcome`, `v`, `repeats`, `seed`, `grouping columns` (`group`, `batch`, `study`, `time`), `stratify`, `nested`, `horizon`, `purge`, `embargo`, `summary` (data.frame of fold sizes), `hash` (reproducibility checksum), `inner` (nested inner splits if `nested = TRUE`), and `coldata` (sample metadata).

Use the `show` method to print a summary, or access slots directly with `@`.

Examples

```
set.seed(1)
df <- data.frame(
  subject = rep(1:10, each = 2),
  outcome = rbinom(20, 1, 0.5),
  x1 = rnorm(20),
  x2 = rnorm(20)
)
splits <- make_split_plan(df, outcome = "outcome",
  mode = "subject_grouped", group = "subject", v = 5)
```

plot_calibration *Plot calibration curve for binomial predictions*

Description

Visualizes observed outcome rates versus predicted probabilities across bins to diagnose calibration (binomial tasks only). Requires `ggplot2`.

Usage

```
plot_calibration(fit, bins = 10, min_bin_n = 5, learner = NULL)
```

Arguments

fit	LeakFit.
bins	Number of probability bins to use.
min_bin_n	Minimum samples per bin shown in the plot.
learner	Optional character scalar. When predictions include multiple learners, selects the learner to summarize.

Value

A list containing the calibration curve, metrics, and a ggplot object.

Examples

```
if (requireNamespace("ggplot2", quietly = TRUE)) {
  set.seed(42)
  df <- data.frame(
    subject = rep(1:15, each = 2),
    outcome = factor(rep(c(0, 1), 15)),
    x1 = rnorm(30),
    x2 = rnorm(30)
  )
  splits <- make_split_plan(df, outcome = "outcome",
                           mode = "subject_grouped", group = "subject",
                           v = 3, progress = FALSE)

  custom <- list(
    glm = list(
      fit = function(x, y, task, weights, ...) {
        stats::glm(y ~ ., data = as.data.frame(x),
                   family = stats::binomial(), weights = weights)
      },
      predict = function(object, newdata, task, ...) {
        as.numeric(stats::predict(object, newdata = as.data.frame(newdata),
                                  type = "response"))
      }
    )
  )
  fit <- fit_resample(df, outcome = "outcome", splits = splits,
                    learner = "glm", custom_learners = custom,
                    metrics = "auc", refit = FALSE, seed = 1)
  plot_calibration(fit, bins = 5)
}
```

Description

Shows performance metrics across confounder strata to assess sensitivity to batch/study effects. Requires ggplot2.

Usage

```
plot_confounder_sensitivity(
  fit,
  confounders = NULL,
  metric = NULL,
  min_n = 10,
  coldata = NULL,
  numeric_bins = 4,
  learner = NULL
)
```

Arguments

fit	LeakFit.
confounders	Character vector of columns in ‘coldata’ to evaluate.
metric	Metric name to compute within each stratum.
min_n	Minimum samples per stratum to display.
coldata	Optional data.frame of sample metadata.
numeric_bins	Number of quantile bins for numeric confounders.
learner	Optional character scalar. When predictions include multiple learners, selects the learner to summarize.

Value

A list containing the sensitivity table and a ggplot object.

Examples

```
if (requireNamespace("ggplot2", quietly = TRUE)) {
  set.seed(42)
  df <- data.frame(
    subject = rep(1:15, each = 2),
    outcome = factor(rep(c(0, 1), 15)),
    batch = factor(rep(c("A", "B", "C"), 10)),
    x1 = rnorm(30),
    x2 = rnorm(30)
  )
  splits <- make_split_plan(df, outcome = "outcome",
                           mode = "subject_grouped", group = "subject",
                           v = 3, progress = FALSE)

  custom <- list(
    glm = list(
      fit = function(x, y, task, weights, ...) {
```

```

      stats::glm(y ~ ., data = as.data.frame(x),
                family = stats::binomial(), weights = weights)
    },
    predict = function(object, newdata, task, ...) {
      as.numeric(stats::predict(object, newdata = as.data.frame(newdata),
                               type = "response"))
    }
  )
)
)
fit <- fit_resample(df, outcome = "outcome", splits = splits,
                  learner = "glm", custom_learners = custom,
                  metrics = "auc", refit = FALSE, seed = 1)
plot_confounder_sensitivity(fit, confounders = "batch", coldata = df)
}

```

plot_fold_balance *Plot fold balance of class counts per fold*

Description

Displays a bar chart of class counts per fold. For binomial tasks, it also overlays the positive proportion to diagnose stratification issues. The positive class is taken from `fit@info$positive_class` when available; otherwise the second factor level is used. For multiclass tasks, the plot shows per-class counts without a proportion line. Only available for classification tasks. Requires `ggplot2`.

Usage

```
plot_fold_balance(fit)
```

Arguments

`fit` LeakFit.

Value

A list containing the fold summary, positive class (if binomial), and a `ggplot` object.

Examples

```

if (requireNamespace("ggplot2", quietly = TRUE)) {
  set.seed(42)
  df <- data.frame(
    subject = rep(1:15, each = 2),
    outcome = factor(rep(c(0, 1), 15)),
    x1 = rnorm(30),
    x2 = rnorm(30)
  )
  splits <- make_split_plan(df, outcome = "outcome",
                           mode = "subject_grouped", group = "subject",

```

```

                                v = 3, progress = FALSE)
custom <- list(
  glm = list(
    fit = function(x, y, task, weights, ...) {
      stats::glm(y ~ ., data = as.data.frame(x),
                 family = stats::binomial(), weights = weights)
    },
    predict = function(object, newdata, task, ...) {
      as.numeric(stats::predict(object, newdata = as.data.frame(newdata),
                                type = "response"))
    }
  )
)
fit <- fit_resample(df, outcome = "outcome", splits = splits,
                   learner = "glm", custom_learners = custom,
                   metrics = "auc", refit = FALSE, seed = 1)
plot_fold_balance(fit)
}

```

plot_overlap_checks *Plot overlap diagnostics between train/test groups*

Description

Checks whether the same group identifiers appear in both the training and test partitions within each resample. This is designed to detect leakage from grouped or repeated-measures data (for example, the same subject, batch, plate, or study appearing on both sides of a fold) when group-wise splitting is expected.

Usage

```
plot_overlap_checks(fit, column = NULL)
```

Arguments

fit	A 'LeakFit' object produced by [fit_resample()]. It must contain the split indices and the associated metadata in 'fit@splits@info\$coldata'. The metadata rows must align with the data used to create the splits.
column	Character scalar naming the metadata column to check (for example "subject" or "batch"). The function compares unique values of this column between train and test within each resample. There is no default: 'NULL' or an unknown column triggers an error. Changing 'column' changes which kind of leakage (subject-level, batch-level, etc.) is tested and therefore the overlap counts.

Details

For each resample in `fit@splits@indices`, the function counts the number of unique values of `column` in the train and test sets and the size of their intersection. Any non-zero overlap indicates that at least one group appears in both train and test for that resample. The check is metadata-based only: it relies on exact matches of the supplied column and does not inspect features or outcomes. It only checks train vs test within each resample, so it will not detect overlaps across different resamples or other leakage mechanisms. Inconsistent IDs or missing values in the metadata can hide or inflate overlaps. `'NA'` values are treated as regular identifiers and will count toward overlap if they appear in both partitions. Requires `ggplot2`.

Value

A list returned invisibly with:

- `'overlap_counts'`: data.frame with one row per resample and columns `'fold'` (resample index in `fit@splits@indices`), `'overlap'` (unique IDs shared by train and test), `'train'` (unique IDs in train), and `'test'` (unique IDs in test).
- `'column'`: the metadata column name used for the check.
- `'plot'`: the ggplot object showing the three count series across folds.

The plot is also printed. When any overlap is detected, the plot adds a warning annotation.

Examples

```
set.seed(1)
df <- data.frame(
  subject = rep(1:6, each = 2),
  outcome = rbinom(12, 1, 0.5),
  x1 = rnorm(12),
  x2 = rnorm(12)
)
splits <- make_split_plan(df, outcome = "outcome",
  mode = "subject_grouped", group = "subject", v = 3)
custom <- list(
  glm = list(
    fit = function(x, y, task, weights, ...) {
      stats::glm(y ~ ., data = as.data.frame(x),
        family = stats::binomial(), weights = weights)
    },
    predict = function(object, newdata, task, ...) {
      as.numeric(stats::predict(object, newdata = as.data.frame(newdata),
        type = "response"))
    }
  )
)
fit <- fit_resample(df, outcome = "outcome", splits = splits,
  learner = "glm", custom_learners = custom,
  metrics = "accuracy", refit = FALSE)
if (requireNamespace("ggplot2", quietly = TRUE)) {
  out <- plot_overlap_checks(fit, column = "subject")
  out$overlap_counts
```

```
}

```

```
plot_perm_distribution
```

Plot permutation distribution for a LeakAudit object

Description

Visualizes the label-permutation metric distribution and marks the observed and permuted-mean values to help assess leakage signals. Requires ggplot2.

Usage

```
plot_perm_distribution(audit)
```

Arguments

audit LeakAudit.

Value

A list containing the observed value, permuted mean, permutation values, and a ggplot object.

Examples

```
if (requireNamespace("ggplot2", quietly = TRUE)) {
  set.seed(42)
  df <- data.frame(
    subject = rep(1:15, each = 2),
    outcome = factor(rep(c(0, 1), 15)),
    x1 = rnorm(30),
    x2 = rnorm(30)
  )
  splits <- make_split_plan(df, outcome = "outcome",
                           mode = "subject_grouped", group = "subject",
                           v = 3, progress = FALSE)

  custom <- list(
    glm = list(
      fit = function(x, y, task, weights, ...) {
        stats::glm(y ~ ., data = as.data.frame(x),
                   family = stats::binomial(), weights = weights)
      },
      predict = function(object, newdata, task, ...) {
        as.numeric(stats::predict(object, newdata = as.data.frame(newdata),
                                 type = "response"))
      }
    )
  )
  fit <- fit_resample(df, outcome = "outcome", splits = splits,
```

```

      learner = "glm", custom_learners = custom,
      metrics = "auc", refit = FALSE, seed = 1)
audit <- audit_leakage(fit, metric = "auc", B = 20)
plot_perm_distribution(audit)
}

```

plot_time_acf

Plot ACF of test predictions for time-series leakage checks

Description

Uses the autocorrelation function of out-of-fold predictions to detect temporal dependence that may indicate leakage. Predictions are ordered by the split time column before computing the ACF. Requires numeric predictions (regression or survival). Requires ggplot2.

Usage

```
plot_time_acf(fit, lag.max = 20)
```

Arguments

fit	LeakFit.
lag.max	maximum lag to show.

Value

A list with the autocorrelation results, lag.max, and a ggplot object.

Examples

```

if (requireNamespace("ggplot2", quietly = TRUE)) {
  set.seed(42)
  df <- data.frame(
    id = 1:30,
    time = seq.Date(as.Date("2020-01-01"), by = "day", length.out = 30),
    y = rnorm(30),
    x1 = rnorm(30),
    x2 = rnorm(30)
  )
  splits <- make_split_plan(df, outcome = "y", mode = "time_series",
    time = "time", v = 3, progress = FALSE)
  custom <- list(
    lm = list(
      fit = function(x, y, task, weights, ...) {
        stats::lm(y ~ ., data = data.frame(y = y, x))
      },
      predict = function(object, newdata, task, ...) {
        as.numeric(stats::predict(object, newdata = as.data.frame(newdata)))
      }
    )
  )
}

```

```

    }
  )
)
fit <- fit_resample(df, outcome = "y", splits = splits,
                  learner = "lm", custom_learners = custom,
                  metrics = "rmse", refit = FALSE, seed = 1)
plot_time_acf(fit, lag.max = 10)
}

```

predict_guard

Apply a fitted GuardFit transformer to new data

Description

Applies the preprocessing steps stored in a GuardFit object to new data without refitting any statistics. This is designed to prevent validation leakage that would occur if imputation, scaling, filtering, or feature selection were recomputed on evaluation data. It enforces the training schema by aligning columns and factor levels, and it errors when a numeric-only training fit receives non-numeric predictors. It does not detect label leakage, duplicate samples, or train/test contamination.

Usage

```
predict_guard(fit, newdata)
```

Arguments

fit	A GuardFit object created by [.guard_fit()]. This required argument (no default) contains the training-time preprocessing settings and statistics. Changing fit (for example, a different imputation method or feature selection step) changes the output columns and values.
newdata	A matrix or data.frame of predictors with one row per sample. This required argument (no default) is transformed using the training-time parameters in fit only. Missing columns are added and filled, extra columns are dropped, and factor levels are aligned to the training levels; if the training fit was numeric-only, non-numeric columns in newdata trigger an error.

Value

A data.frame of transformed predictors with the same number of rows as newdata. Column order and content match the training pipeline and may include derived features (one-hot encodings, missingness indicators, or PCA components). This output is not a prediction; it is intended as input to a downstream model and assumes the training-time preprocessing is valid for the new data.

Examples

```
x_train <- data.frame(a = c(1, 2, NA, 4), b = c(10, 11, 12, 13))
fit <- .guard_fit(
  x_train,
  y = c(0.1, 0.2, 0.3, 0.4),
  steps = list(impute = list(method = "median")),
  task = "gaussian"
)
x_new <- data.frame(a = c(NA, 5), b = c(9, 14))
out <- predict_guard(fit, x_new)
out
```

show,LeakSplits-method

Display summary for LeakSplits objects

Description

Prints fold counts, sizes, and hash metadata for quick inspection.

Usage

```
## S4 method for signature 'LeakSplits'
show(object)
```

Arguments

object LeakSplits object.

Value

No return value, called for side effects (prints a summary to the console showing mode, fold count, repeats, outcome, stratification status, nested status, per-fold train/test sizes, and the reproducibility hash).

Examples

```
df <- data.frame(
  subject = rep(1:10, each = 2),
  outcome = rbinom(20, 1, 0.5),
  x1 = rnorm(20),
  x2 = rnorm(20)
)
splits <- make_split_plan(df, outcome = "outcome",
  mode = "subject_grouped", group = "subject", v = 5)
show(splits)
```

`simulate_leakage_suite`*Simulate leakage scenarios and audit results*

Description

Simulates synthetic binary classification datasets with optional leakage mechanisms, fits a model using a leakage-aware cross-validation scheme, and summarizes the permutation-gap audit for each Monte Carlo seed. The suite is designed to surface validation failures such as subject overlap across folds, batch-confounded outcomes, global normalization/summary leakage, and time-series look-ahead. The output is a per-seed summary of observed CV performance and its gap versus a label-permutation null; it does not return fitted models or the full audit object. Results are limited to the built-in data generator and leakage types implemented here, and should be interpreted as a simulation-based sanity check rather than a comprehensive leakage detector for real data.

Usage

```
simulate_leakage_suite(  
  n = 500,  
  p = 20,  
  prevalence = 0.5,  
  mode = c("subject_grouped", "batch_blocked", "study_loocv", "time_series"),  
  learner = c("glmnet", "ranger"),  
  leakage = c("none", "subject_overlap", "batch_confounded", "peek_norm", "lookahead"),  
  preprocess = NULL,  
  rho = 0,  
  K = 5,  
  repeats = 1,  
  horizon = 0,  
  B = 200,  
  seeds = 1:10,  
  parallel = FALSE,  
  signal_strength = 1,  
  verbose = FALSE  
)
```

Arguments

<code>n</code>	Integer scalar. Number of samples to simulate (default 500). Larger values stabilize the Monte Carlo summary but increase runtime.
<code>p</code>	Integer scalar. Number of baseline predictors before any leakage feature is added (default 20). Increasing <code>p</code> changes the signal-to-noise ratio and increases fitting time.
<code>prevalence</code>	Numeric scalar in (0, 1). Target prevalence of class 1 in the simulated outcome (default 0.5). Changing this alters class imbalance and can affect AUC and the permutation gap.

mode	Character scalar. Cross-validation scheme passed to <code>make_split_plan()</code> ; one of "subject_grouped", "batch_blocked", "study_loocv", "time_series". Defaults to "subject_grouped". This controls how samples are grouped into folds (by subject, batch, study, or time) and therefore which leakage mechanisms are realistically challenged.
learner	Character scalar. Base learner, "glmnet" (default) or "ranger". Requires the corresponding package in <code>Suggests</code> . Switching learners changes the fitted model, runtime, and performance.
leakage	Character scalar. Leakage mechanism to inject; one of "none", "subject_overlap", "batch_confounded", "peek_norm", "lookahead". Leakage is added as an extra predictor: "subject_overlap" adds per-subject mean outcome, "batch_confounded" adds per-batch mean outcome, "peek_norm" adds the globally normalized (z-scored) outcome, and "lookahead" adds the next-time outcome. Changing this controls whether and how leakage is present.
preprocess	Optional preprocessing list or recipe passed to <code>[fit_resample()]</code> . When NULL (default), the simulator uses the <code>fit_resample</code> defaults; for "peek_norm" leakage, normalization is set to "none" to avoid attenuating the constant leakage feature.
rho	Numeric scalar in [-1, 1]. AR(1)-style autocorrelation applied to each predictor across row order (default 0). Higher absolute values increase serial correlation and make time-ordered leakage more pronounced.
K	Integer scalar. Number of folds/partitions (default 5). Used as the fold count for "subject_grouped" and "batch_blocked", and as the number of rolling partitions for "time_series". Ignored for "study_loocv" (folds equal the number of studies).
repeats	Integer scalar ≥ 1 . Number of repeated CV runs for "subject_grouped" and "batch_blocked" (default 1). Increasing repeats increases the number of folds and runtime. Ignored for "study_loocv" and "time_series".
horizon	Numeric scalar ≥ 0 . Minimum time gap enforced between train and test for "time_series" splits (default 0). Larger values make the split more conservative and can reduce leakage from temporal proximity.
B	Integer scalar ≥ 1 . Number of permutations used by <code>audit_leakage()</code> to compute the permutation gap and p-value (default 200). Larger values yield more stable p-values but increase runtime.
seeds	Integer vector. Monte Carlo seeds (default 1:10). One row of output is produced per seed; changing seeds changes the simulated datasets and splits.
parallel	Logical scalar. If TRUE, evaluates seeds in parallel using <code>future.apply</code> (if installed). Results are identical to sequential execution; only runtime changes.
signal_strength	Numeric scalar. Scales the linear predictor before sampling outcomes (default 1). Larger values increase class separation and tend to increase AUC; smaller values make the task harder.
verbose	Logical scalar. If TRUE, prints progress messages for each seed. Does not affect results.

Details

The generator draws p standard normal predictors, builds a linear predictor from the first $\min(5, p)$ features, scales it by `signal_strength`, and samples a binary outcome to achieve the requested prevalence. Outcomes are returned as a two-level factor, so the audited metric is AUC. Simulated metadata include `subject`, `batch`, `study`, and `time` fields used by `mode` to create leakage-aware splits. Leakage mechanisms are injected by adding a single extra predictor as described in `leakage`. Parallel execution uses `future.apply` when installed and does not change results.

Value

A `LeakSimResults` data frame with one row per seed and columns:

- `seed`: seed used for data generation, splitting, and auditing.
- `metric_obs`: observed CV performance (AUC for this simulation).
- `gap`: permutation-gap statistic (observed minus permutation mean).
- `p_value`: permutation p-value for the gap.
- `leakage`: leakage scenario used.
- `mode`: CV mode used.

Only the permutation-gap summary is returned; fitted models, predictions, and other audit components are not included.

Note

This function is a general-purpose utility and its data-generation logic intentionally differs from the custom simulation used in the `bioLeak` manuscript (`'paper/run_simulation.R'`). Specific differences:

- **peek_norm leakage**: this function uses a z-scored binary outcome as the leak feature; the manuscript uses a noisy continuous version (`as.numeric(y) + rnorm(n, 0, 0.3)`).
- **lookahead leakage**: this function shifts the binary outcome (`c(y[-1], y[n])`); the manuscript shifts a continuous biomarker (`linpred + noise`).
- **signal generation**: this function applies AR correlation to predictors via `rho`; the manuscript adds AR(1) noise directly to the linear predictor.
- **audit settings**: the manuscript uses `perm_refit = FALSE` and `perm_stratify = TRUE`; this function uses `perm_refit = "auto"` and the `perm_stratify` default (`FALSE`).

Users wishing to reproduce manuscript figures should run `'paper/run_simulation.R'` directly rather than calling this function.

Examples

```
if (requireNamespace("glmnet", quietly = TRUE)) {
  set.seed(1)
  res <- simulate_leakage_suite(
    n = 120, p = 6, prevalence = 0.4,
    mode = "subject_grouped",
    learner = "glmnet",
```

```

    leakage = "subject_overlap",
    K = 3, repeats = 1,
    B = 50, seeds = 1,
    parallel = FALSE
  )
  # One row per seed with observed AUC, permutation gap, and p-value
  res
}

```

```
summary.LeakAudit      Summarize a leakage audit
```

Description

Prints a concise, human-readable report for a ‘LeakAudit’ object produced by [audit_leakage()]. The summary surfaces four diagnostics when available: label-permutation gap (prediction-label association by default), batch/study association tests (metadata aligned with fold splits), target leakage scan (features strongly associated with the outcome), and near-duplicate detection (high similarity in ‘X_ref’). The output reflects the stored audit results only; it does not recompute any tests.

Usage

```
## S3 method for class 'LeakAudit'
summary(object, digits = 3, ...)
```

Arguments

object	A ‘LeakAudit’ object from [audit_leakage()]. The summary reads stored results from ‘object’ and prints them to the console.
digits	Integer number of digits to show when formatting numeric statistics in the console output. Defaults to ‘3’. Increasing ‘digits’ shows more precision; decreasing it shortens the printout without changing the underlying values.
...	Unused. Included for S3 method compatibility; additional arguments are ignored.

Details

The permutation test quantifies prediction-label association when using fixed predictions; refit-based permutations require ‘perm_refit = TRUE’ (or “auto” with refit data). It does not by itself prove or rule out leakage. Batch association flags metadata that align with fold assignment; this may reflect study design rather than leakage. Target leakage scan uses univariate feature-outcome associations and can miss multivariate proxies, interaction leakage, or features not included in ‘X_ref’. The multivariate scan (enabled by default for supported tasks) reports an additional model-based score. Duplicate detection only considers the provided ‘X_ref’ features and the similarity threshold used during [audit_leakage()]. By default, ‘duplicate_scope = "train_test"’ filters to pairs that cross train/test; set ‘duplicate_scope = "all"’ to include within-fold duplicates. Sections are reported as “not available” when the corresponding audit component was not computed.

Value

Invisibly returns 'object' after printing the summary.

See Also

[plot_perm_distribution()], [plot_fold_balance()], [plot_overlap_checks()]

Examples

```
set.seed(1)
df <- data.frame(
  subject = rep(1:6, each = 2),
  outcome = rbinom(12, 1, 0.5),
  x1 = rnorm(12),
  x2 = rnorm(12)
)
splits <- make_split_plan(df, outcome = "outcome",
  mode = "subject_grouped", group = "subject", v = 3)
custom <- list(
  glm = list(
    fit = function(x, y, task, weights, ...) {
      stats::glm(y ~ ., data = as.data.frame(x),
        family = stats::binomial(), weights = weights)
    },
    predict = function(object, newdata, task, ...) {
      as.numeric(stats::predict(object, newdata = as.data.frame(newdata),
        type = "response"))
    }
  )
)
fit <- fit_resample(df, outcome = "outcome", splits = splits,
  learner = "glm", custom_learners = custom,
  metrics = "auc", refit = FALSE, seed = 1)
audit <- audit_leakage(fit, metric = "auc", B = 5,
  X_ref = df[, c("x1", "x2")], seed = 1)
summary(audit) # prints the audit report and returns `audit` invisibly
```

summary.LeakDeltaLSI *Summarize a LeakDeltaLSI object*

Description

Prints a human-readable summary of the Delta LSI analysis comparing leaky vs guarded evaluation pipelines.

Usage

```
## S3 method for class 'LeakDeltaLSI'
summary(object, digits = 3L, ...)
```

Arguments

object	A LeakDeltaLSI object from <code>delta_lsi</code> .
digits	Integer. Number of decimal places to show (default 3).
...	Unused.

Value

Invisibly returns object.

summary.LeakFit	<i>Summarize a LeakFit object</i>
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Description

Prints a compact console report for a [LeakFit] object created by [fit_resample()]. The report lists task/outcome metadata, learners, total folds, and cross-validated metrics summarized as mean and standard deviation across completed folds, plus a small audit table with per-fold train/test sizes and retained feature counts.

Usage

```
## S3 method for class 'LeakFit'
summary(object, digits = 3, ...)
```

Arguments

object	A [LeakFit] object returned by [fit_resample()]. It should contain ‘metric_summary’ and ‘audit’ slots; missing entries result in empty sections in the printed report.
digits	Integer scalar. Number of decimal places to print in numeric summary tables. Defaults to 3; affects printed output only, not the returned data.
...	Unused. Included for S3 method compatibility; changing these values has no effect.

Details

This summary is meant for quick sanity checks of the resampling setup and performance. It does not run leakage diagnostics and will not detect target leakage, duplicate samples, or batch/study confounding; use [audit_leakage()] or ‘summary()’ on a [LeakAudit] object for those checks.

Value

Invisibly returns ‘object@metric_summary’, a data frame of per-learner metric means and standard deviations computed across folds. This function does not recompute metrics.

Examples

```

set.seed(1)
df <- data.frame(
  subject = rep(1:6, each = 2),
  outcome = factor(rep(c(0, 1), each = 6)),
  x1 = rnorm(12),
  x2 = rnorm(12)
)
splits <- make_split_plan(
  df,
  outcome = "outcome",
  mode = "subject_grouped",
  group = "subject",
  v = 3,
  stratify = TRUE,
  progress = FALSE
)
custom <- list(
  glm = list(
    fit = function(x, y, task, weights, ...) {
      stats::glm(y ~ ., data = data.frame(y = y, x),
        family = stats::binomial(), weights = weights)
    },
    predict = function(object, newdata, task, ...) {
      as.numeric(stats::predict(object,
        newdata = as.data.frame(newdata),
        type = "response"))
    }
  )
)
fit <- fit_resample(df, outcome = "outcome", splits = splits,
  learner = "glm", custom_learners = custom,
  metrics = "auc", seed = 1)
summary_df <- summary(fit)
summary_df

```

summary.LeakTune

Summarize a nested tuning result

Description

Prints a concise report for a ‘LeakTune’ object produced by [tune_resample()]. The report highlights the tuning strategy, selection metric, and cross-validated performance across outer folds, plus a glimpse of the selected hyperparameters.

Usage

```

## S3 method for class 'LeakTune'
summary(object, digits = 3, ...)

```

Arguments

object	A [LeakTune] object returned by [tune_resample()].
digits	Integer scalar. Number of decimal places to print in numeric summary tables. Defaults to 3.
...	Unused. Included for S3 method compatibility.

Value

Invisibly returns 'object\$metric_summary', the data frame of per-learner metric means and standard deviations computed across outer folds.

tune_resample	<i>Leakage-aware nested tuning with tidymodels</i>
---------------	----------------------------------------------------

Description

Runs nested cross-validation for hyperparameter tuning using leakage-aware splits. Inner resamples are constructed from each outer training fold to avoid information leakage during tuning. Requires tidymodels tuning packages and a workflow or recipe-based preprocessing. Survival tasks are not yet supported.

Usage

```
tune_resample(
  x,
  outcome,
  splits,
  learner,
  preprocess = NULL,
  grid = 10,
  metrics = NULL,
  positive_class = NULL,
  selection = c("best", "one_std_err"),
  selection_metric = NULL,
  inner_v = NULL,
  inner_repeats = 1,
  inner_seed = NULL,
  control = NULL,
  parallel = FALSE,
  refit = FALSE,
  seed = 1,
  split_cols = "auto",
  tune_threshold = FALSE,
  threshold_grid = seq(0.1, 0.9, by = 0.05),
  threshold_metric = "accuracy"
)
```

Arguments

<code>x</code>	SummarizedExperiment or matrix/data.frame.
<code>outcome</code>	Outcome column name (if <code>x</code> is SE or data.frame).
<code>splits</code>	LeakSplits object defining the outer resamples. If the splits do not already include inner folds, they are created from each outer training fold using the same split metadata. <code>rsample</code> splits must already include inner folds.
<code>learner</code>	A parsnip model_spec with tunable parameters, or a workflows workflow. When a model_spec is provided, a workflow is built using <code>'preprocess'</code> or a formula.
<code>preprocess</code>	Optional <code>'recipes::recipe'</code> . Required when you need preprocessing for tuning. Ignored when <code>'learner'</code> is already a workflow. Recipe/workflow leakage guardrails run before tuning; configure policy via <code>options(bioLeak.validation_mode = "warn" "error" "off")</code> .
<code>grid</code>	Tuning grid passed to <code>'tune::tune_grid()'</code> . Can be a data.frame or an integer size.
<code>metrics</code>	Character vector of metric names (<code>'auc'</code> , <code>'pr_auc'</code> , <code>'accuracy'</code> , <code>'macro_f1'</code> , <code>'log_loss'</code> , <code>'rmse'</code>) or a yardstick metric set/list. Metrics are computed with yardstick; unsupported metrics are dropped with a warning. For binomial tasks, if any inner assessment fold contains a single class, probability metrics (<code>'auc'</code> , <code>'roc_auc'</code> , <code>'pr_auc'</code>) are dropped for tuning with a warning.
<code>positive_class</code>	Optional value indicating the positive class for binomial outcomes. When set, the outcome levels are reordered so the positive class is second.
<code>selection</code>	Selection rule for tuning, either <code>"best"</code> or <code>"one_std_err"</code> .
<code>selection_metric</code>	Metric name used for selecting hyperparameters. Defaults to the first metric in <code>'metrics'</code> . If the chosen metric yields no valid results, the first available metric is used with a warning.
<code>inner_v</code>	Optional number of folds for inner CV when inner splits are not precomputed. Defaults to the outer <code>'v'</code> .
<code>inner_repeats</code>	Optional number of repeats for inner CV when inner splits are not precomputed. Defaults to 1.
<code>inner_seed</code>	Optional seed for inner split generation when inner splits are not precomputed. Defaults to the outer split seed.
<code>control</code>	Optional <code>'tune::control_grid()'</code> settings for tuning.
<code>parallel</code>	Logical; passed to <code>[fit_resample()]</code> when evaluating outer folds (single-fold, no refit).
<code>refit</code>	Logical; if TRUE, refits a final tuned workflow on the full dataset using aggregated hyperparameters across all outer folds (median for numeric parameters, majority vote for categorical). This avoids nested-CV leakage that would occur from selecting a single fold's params.
<code>seed</code>	Integer seed for reproducibility.
<code>split_cols</code>	Optional named list/character vector or <code>"auto"</code> (default) overriding group/batch/study/time column names when <code>'splits'</code> is an <code>rsample</code> object and its attributes are missing. <code>"auto"</code> falls back to common metadata column names (e.g., <code>'group'</code> , <code>'subject'</code> , <code>'batch'</code> , <code>'study'</code> , <code>'time'</code>). Supported names are <code>'group'</code> , <code>'batch'</code> , <code>'study'</code> , and <code>'time'</code> .

tune_threshold	Logical; when ‘TRUE’ for binomial tasks, selects a probability threshold from inner-fold predictions and applies it only to the corresponding outer-fold evaluation.
threshold_grid	Numeric vector of thresholds in ‘[0, 1]’ considered when ‘tune_threshold = TRUE’.
threshold_metric	Metric used to pick thresholds when ‘tune_threshold = TRUE’. Supported values are “accuracy”, “balanced_accuracy”, and “f1”, or a custom function with signature ‘function(truth, pred_class, prob, threshold)’.

Value

A list of class “LeakTune” with components:

metrics	Outer-fold metrics.
metric_summary	Mean/SD metrics across outer folds with columns learner, and <metric>_mean and <metric>_sd for each metric.
best_params	Best hyperparameters per outer fold.
inner_results	List of inner tuning results.
outer_fits	List of outer LeakFit objects.
thresholds	Per-fold threshold choices when threshold tuning is enabled.
fold_status	Outer-fold status log with stage, status, reason, and notes.
final_model	Optional final workflow fit when ‘refit = TRUE’.
info	Metadata about the tuning run.

Examples

```
if (requireNamespace("tune", quietly = TRUE) &&
    requireNamespace("recipes", quietly = TRUE) &&
    requireNamespace("glmnet", quietly = TRUE) &&
    requireNamespace("rsample", quietly = TRUE) &&
    requireNamespace("workflows", quietly = TRUE) &&
    requireNamespace("yardstick", quietly = TRUE) &&
    requireNamespace("dials", quietly = TRUE)) {
  df <- data.frame(
    subject = rep(1:10, each = 2),
    outcome = factor(rep(c(0, 1), each = 10)),
    x1 = rnorm(20),
    x2 = rnorm(20)
  )
  splits <- make_split_plan(df, outcome = "outcome",
                           mode = "subject_grouped", group = "subject",
                           v = 3, nested = TRUE, stratify = TRUE)
  spec <- parsnip::logistic_reg(penalty = tune::tune(), mixture = 1) |>
    parsnip::set_engine("glmnet")
  rec <- recipes::recipe(outcome ~ x1 + x2, data = df)
  tuned <- tune_resample(df, outcome = "outcome", splits = splits,
                        learner = spec, preprocess = rec, grid = 5)
```

```
  tuned$metric_summary  
}
```

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