1 Introduction

This paper contains examples of various features from \LaTeX.

2 Enumeration of Hamiltonian paths in a graph

Let $A = (a_{ij})$ be the adjacency matrix of graph $G$. The corresponding Kirchhoff matrix $K = (k_{ij})$ is obtained from $A$ by replacing in $-A$ each diagonal entry by the degree of its corresponding vertex; i.e., the $i$th diagonal entry is identified with the degree of the $i$th vertex. It is well known that

$$\det K(i|i) = \text{the number of spanning trees of } G,$$  

where $K(i|i)$ is the $i$th principal submatrix of $K$.

Let $C_{i(j)}$ be the set of graphs obtained from $G$ by attaching edge $(v_i v_j)$ to each spanning tree of $G$. Denote by $C_i = \bigcup_j C_{i(j)}$. It is obvious that the collection of Hamiltonian cycles is a subset of $C_i$. Note that the cardinality of $C_i$ is $k_{ii} \det K(i|i)$. Let $\hat{X} = \{\hat{x}_1, \ldots, \hat{x}_n\}$.

Define multiplication for the elements of $\hat{X}$ by

$$\hat{x}_i \hat{x}_j = \hat{x}_j \hat{x}_i, \quad \hat{x}_i^2 = 0, \quad i, j = 1, \ldots, n.$$  

Let $\hat{k}_{ij} = k_{ij} \hat{x}_j$ and $\hat{k}_{ij} = -\sum_{j \neq i} \hat{k}_{ij}$. Then the number of Hamiltonian cycles $H_c$ is given by the relation [8]

$$\left( \prod_{j=1}^n \hat{x}_j \right) H_c = \frac{1}{2} \hat{k}_{ij} \det \hat{K}(i|i), \quad i = 1, \ldots, n.$$  

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The task here is to express (3) in a form free of any \( \hat{x}_i \), \( i = 1, \ldots, n \). The result also leads to the resolution of enumeration of Hamiltonian paths in a graph.

It is well known that the enumeration of Hamiltonian cycles and paths in a complete graph \( K_n \) and in a complete bipartite graph \( K_{n_1, n_2} \) can only be found from first combinatorial principles [4]. One wonders if there exists a formula which can be used very efficiently to produce \( K_n \) and \( K_{n_1, n_2} \). Recently, using Lagrangian methods, Goulden and Jackson have shown that \( H_c \) can be expressed in terms of the determinant and permanent of the adjacency matrix [3]. However, the formula of Goulden and Jackson determines neither \( K_n \) nor \( K_{n_1, n_2} \) effectively. In this paper, using an algebraic method, we parametrize the adjacency matrix. The resulting formula also involves the determinant and permanent, but it can easily be applied to \( K_n \) and \( K_{n_1, n_2} \). In addition, we eliminate the permanent from \( H_c \) and show that \( H_c \) can be represented by a determinantal function of multivariables, each variable with domain \( \{0, 1\} \). Furthermore, we show that \( H_c \) can be written by number of spanning trees of subgraphs. Finally, we apply the formulas to a complete multigraph \( K_{n_1 \ldots n_p} \).

The conditions \( a_{ij} = a_{ji}, i, j = 1, \ldots, n \), are not required in this paper. All formulas can be extended to a digraph simply by multiplying \( H_c \) by 2.

3 Main Theorem

\textbf{Notation.} For \( p, q \in P \) and \( n \in \omega \) we write \( (q, n) \leq (p, n) \) if \( q \leq p \) and \( A_{q,n} = A_{p,n} \).

\begin{notation}
$\begin{align*}
\text{For } p, q \in P \text{ and } n \in \omega \\
\text{we write } (q, n) \leq (p, n) \text{ if } q \leq p \text{ and } A_{q,n} = A_{p,n}.
\end{align*}$
\end{notation}

Let \( B = (b_{ij}) \) be an \( n \times n \) matrix. Let \( n = \{1, \ldots, n\} \). Using the properties of (2), it is readily seen that

\begin{lemma}
\begin{equation}
\prod_{i \in n} \left( \sum_{j \in n} b_{ij} \hat{x}_j \right) = \left( \prod_{i \in n} \hat{x}_i \right) \text{per } B \tag{4}
\end{equation}
\end{lemma}

where \text{per } B \text{ is the permanent of } B.

Let \( \hat{Y} = \{\hat{y}_1, \ldots, \hat{y}_n\} \). Define multiplication for the elements of \( \hat{Y} \) by

\begin{equation}
\hat{y}_i \hat{y}_j + \hat{y}_j \hat{y}_i = 0, \quad i, j = 1, \ldots, n. \tag{5}
\end{equation}

Then, it follows that

\begin{lemma}
\begin{equation}
\prod_{i \in n} \left( \sum_{j \in n} b_{ij} \hat{y}_j \right) = \left( \prod_{i \in n} \hat{y}_i \right) \det B. \tag{6}
\end{equation}
\end{lemma}
Note that all basic properties of determinants are direct consequences of Lemma 3.2. Write
\[ \sum_{j \in \mathbb{N}} b_{ij} \hat{y}_j = \sum_{j \in \mathbb{N}} b_{ij}^{(\lambda)} \hat{y}_j + (b_{ii} - \lambda_i) \hat{y}_i \hat{y} \] (7)
where
\[ b_{ii}^{(\lambda)} = \lambda_i, \quad b_{ij}^{(\lambda)} = b_{ij}, \quad i \neq j. \] (8)
Let \( B^{(\lambda)} = (b_{ij}^{(\lambda)}) \). By (6) and (7), it is straightforward to show the following result:

**Theorem 3.3.**
\[ \det B = \sum_{I_i} \prod_{1 \leq n} (b_{ii} - \lambda_i) \det B^{(\lambda)}(I_i|I_i), \] (9)
where \( I_i = \{i_1, \ldots, i_l\} \) and \( B^{(\lambda)}(I_i|I_i) \) is the principal submatrix obtained from \( B^{(\lambda)} \) by deleting its \( i_1, \ldots, i_l \) rows and columns.

**Remark 3.1.** Let \( M \) be an \( n \times n \) matrix. The convention \( M(\mathbb{N}|\mathbb{N}) = 1 \) has been used in (9) and hereafter.

Before proceeding with our discussion, we pause to note that Theorem 3.3 yields immediately a fundamental formula which can be used to compute the coefficients of a characteristic polynomial [9]:

**Corollary 3.4.** Write \[ \det(B - xI) = \sum_{l=0}^{n} (-1)^l b_l x^l. \] Then
\[ b_l = \sum_{I_i \subseteq \mathbb{N}} \det B(I_i|I_i). \] (10)
Let
\[
K(t, t_1, \ldots, t_n) = \begin{pmatrix}
D_1 t & -a_{12} t_2 & \cdots & -a_{1n} t_n \\
-a_{21} t_1 & D_2 t & \cdots & -a_{2n} t_n \\
\hdotsfor[2]{4} \\
-a_{n1} t_1 & -a_{n2} t_2 & \cdots & D_n t
\end{pmatrix},
\]
\[
\begin{pmatrix}
D_1 t & -a_{12} t_2 & \cdots & -a_{1n} t_n \\
-a_{21} t_1 & D_2 t & \cdots & -a_{2n} t_n \\
\hdotsfor[2]{4} \\
-a_{n1} t_1 & -a_{n2} t_2 & \cdots & D_n t
\end{pmatrix}
\]
where
\[ D_i = \sum_{j \in \mathbb{N}} a_{ij} t_j, \quad i = 1, \ldots, n. \] (12)
Set
\[ D(t_1, \ldots, t_n) = \frac{\delta}{\delta t_1} \det K(t, t_1, \ldots, t_n)|_{t=1}. \]
Then
\[ D(t_1, \ldots, t_n) = \sum_{i \in \mathbf{n}} D_i \det \mathbf{K}(t = 1, t_1, \ldots, t_n; i|i) \tag{13} \]

where \( \mathbf{K}(t = 1, t_1, \ldots, t_n; i|i) \) is the \( i \)th principal submatrix of \( \mathbf{K}(t = 1, t_1, \ldots, t_n) \).

Theorem 3.3 leads to
\[ \det \mathbf{K}(t_1, t_1, \ldots, t_n) = \sum_{I \in \mathbf{n}} (-1)^{|I|} \prod_{i \in I} t_i \prod_{j \in I} (D_j + \lambda_j t_j) \det \mathbf{A}^{(\lambda)}(I|I). \tag{14} \]

Note that
\[ \det \mathbf{K}(t = 1, t_1, \ldots, t_n) = \sum_{I \in \mathbf{n}} (-1)^{|I|} \prod_{i \in I} t_i \prod_{j \in I} (D_j + \lambda_j t_j) \det \mathbf{A}^{(\lambda)}(I|I) = 0. \tag{15} \]

Let \( t_i = \hat x_i, i = 1, \ldots, n \). Lemma 3.1 yields
\begin{equation}
\left( \sum_{i \in \mathbf{n}} a_{l i} x_i \right) \det \mathbf{K}(t = 1, x_1, \ldots, x_n; l |l) = \left( \prod_{i \in \mathbf{n}} \hat x_i \right) \sum_{I \subseteq \mathbf{n} - \{l \}} (-1)^{|I|} \text{per} \mathbf{A}^{(\lambda)}(I|I) \det \mathbf{A}^{(\lambda)}(\overline{I} \cup \{l \} | \overline{I} \cup \{l \}). \tag{16} \end{equation}

By (3), (6), and (7), we have

\[ H_c = \frac{1}{2n} \sum_{l=0}^{n} (-1)^l D_l, \tag{17} \]

where
\[ D_l = \sum_{I \in \mathbf{n}} D(t_1, \ldots, t_n) |_{t_i = 0, \text{ if } i \in t_l} 1, \text{ otherwise } i = 1, \ldots, n. \tag{18} \]

4 Application

We consider here the applications of Theorems 5.1 and 5.2 to a complete multipartite graph \( K_{n_1 \ldots n_p} \). It can be shown that the number of spanning trees of...
$K_{n_1 \ldots n_p}$ may be written

$$T = n^{p-2} \prod_{i=1}^{p} (n - n_i)^{n_i - 1} \quad (19)$$

where

$$n = n_1 + \cdots + n_p. \quad (20)$$

It follows from Theorems 5.1 and 5.2 that

$$H_c = \frac{1}{2n} \sum_{l=0}^{n} \frac{(-1)^l (n - l)^{p-2}}{l_1 + \cdots + l_p = l} \prod_{i=1}^{p} \binom{n_i}{l_i} \cdot [(n - l) - (n_i - l_i)]^{n_i - l_i} \cdot [(n - l)^2 - \sum_{j=1}^{p} (n_i - l_i)^2]. \quad (21)$$

\[ \ldots \binom{n_i}{l_i} \{1 \_i\} \\]

and

$$H_c = \frac{1}{2} \sum_{l=0}^{n-1} (-1)^l (n - l)^{p-2} \sum_{l_1 + \cdots + l_p = l} \prod_{i=1}^{p} \binom{n_i}{l_i} \cdot [(n - l) - (n_i - l_i)]^{n_i - l_i} \cdot \left(1 - \frac{l_p}{n_p}\right) \frac{(n - l) - (n_p - l_p)}{[n - l - (n_p - l_p)]}. \quad (22)$$

The enumeration of $H_c$ in a $K_{n_1 \ldots n_p}$ graph can also be carried out by Theorem 7.2 or 7.3 together with the algebraic method of (2). Some elegant representations may be obtained. For example, $H_c$ in a $K_{n_1 n_2 n_3}$ graph may be written

$$H_c = \frac{n_1! n_2! n_3!}{n_1 + n_2 + n_3} \sum_{i} \left[ \binom{n_1}{i} \binom{n_2}{n_3 - n_1 + i} \binom{n_3}{n_3 - n_2 + i} + \binom{n_1 - 1}{i} \binom{n_2 - 1}{n_3 - n_1 + i} \binom{n_3 - 1}{n_3 - n_2 + i} \right]. \quad (23)$$

## 5 Secret Key Exchanges

Modern cryptography is fundamentally concerned with the problem of secure private communication. A Secret Key Exchange is a protocol where Alice and Bob, having no secret information in common to start, are able to agree on a common secret key, conversing over a public channel. The notion of a Secret Key Exchange protocol was first introduced in the seminal paper of Diffie and Hellman [1]. [1] presented a concrete implementation of a Secret Key Exchange protocol, dependent on a specific assumption (a variant on the discrete log), specially tailored to yield Secret Key Exchange. Secret Key Exchange is
of course trivial if trapdoor permutations exist. However, there is no known implementation based on a weaker general assumption.

The concept of an informationally one-way function was introduced in [5]. We give only an informal definition here:

**Definition 5.1.** A polynomial time computable function \( f = \{ f_k \} \) is informationally one-way if there is no probabilistic polynomial time algorithm which (with probability of the form \( 1 - k^{-e} \) for some \( e > 0 \)) returns on input \( y \in \{0, 1\}^k \) a random element of \( f^{-1}(y) \).

In the non-uniform setting [5] show that these are not weaker than one-way functions:

**Theorem 5.1** ([5] (non-uniform)). The existence of informationally one-way functions implies the existence of one-way functions.

We will stick to the convention introduced above of saying “non-uniform” before the theorem statement when the theorem makes use of non-uniformity. It should be understood that if nothing is said then the result holds for both the uniform and the non-uniform models.

It now follows from Theorem 5.1 that

**Theorem 5.2** (non-uniform). Weak SKE implies the existence of a one-way function.

More recently, the polynomial-time, interior point algorithms for linear programming have been extended to the case of convex quadratic programs [11, 13], certain linear complementarity problems [7, 10], and the nonlinear complementarity problem [6]. The connection between these algorithms and the classical Newton method for nonlinear equations is well explained in [7].

6 Review

We begin our discussion with the following definition:

**Definition 6.1.** A function \( H : \mathbb{R}^n \to \mathbb{R}^n \) is said to be \( B \)-differentiable at the point \( z \) if (i) \( H \) is Lipschitz continuous in a neighborhood of \( z \), and (ii) there exists a positive homogeneous function \( BH(z) : \mathbb{R}^n \to \mathbb{R}^n \), called the \( B \)-derivative of \( H \) at \( z \), such that

\[
\lim_{v \to 0} \frac{H(z + v) - H(z) - BH(z)v}{\|v\|} = 0.
\]

The function \( H \) is \( B \)-differentiable in set \( S \) if it is \( B \)-differentiable at every point in \( S \). The \( B \)-derivative \( BH(z) \) is said to be strong if

\[
\lim_{(v, v') \to (0, 0)} \frac{H(z + v) - H(z + v') - BH(z)(v - v')}{\|v - v'\|} = 0.
\]
Lemma 6.1. There exists a smooth function $\psi_0(z)$ defined for $|z| > 1 - 2a$ satisfying the following properties:

(i) $\psi_0(z)$ is bounded above and below by positive constants $c_1 \leq \psi_0(z) \leq c_2$.

(ii) If $|z| > 1$, then $\psi_0(z) = 1$.

(iii) For all $z$ in the domain of $\psi_0$, $\Delta_0 \ln \psi_0 \geq 0$.

(iv) If $1 - 2a < |z| < 1 - a$, then $\Delta_0 \ln \psi_0 \geq c_3 > 0$.

Proof. We choose $\psi_0(z)$ to be a radial function depending only on $r = |z|$. Let $h(r) \geq 0$ be a suitable smooth function satisfying $h(r) \geq c_3$ for $1 - 2a < |z| < 1 - a$, and $h(r) = 0$ for $|z| > 1 - \frac{a}{2}$. The radial Laplacian

$$\Delta_0 \ln \psi_0(r) = \left(\frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr}\right) \ln \psi_0(r)$$

has smooth coefficients for $r > 1 - 2a$. Therefore, we may apply the existence and uniqueness theory for ordinary differential equations. Simply let $\ln \psi_0(r)$ be the solution of the differential equation

$$\left(\frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr}\right) \ln \psi_0(r) = h(r)$$

with initial conditions given by $\ln \psi_0(1) = 0$ and $\ln' \psi_0(1) = 0$.

Next, let $D_\nu$ be a finite collection of pairwise disjoint disks, all of which are contained in the unit disk centered at the origin in $C$. We assume that $D_\nu = \{z \mid |z - z_\nu| < \delta\}$. Suppose that $D_\nu(a)$ denotes the smaller concentric disk $D_\nu(a) = \{z \mid |z - z_\nu| \leq (1 - 2a)\delta\}$. We define a smooth weight function $\Phi_0(z)$ for $z \in C - \bigcup_\nu D_\nu(a)$ by setting $\Phi_0(z) = 1$ when $z \notin \bigcup_\nu D_\nu$ and $\Phi_0(z) = \psi_0((z - z_\nu)/\delta)$ when $z$ is an element of $D_\nu$. It follows from Lemma 6.1 that $\Phi_0$ satisfies the properties:

(i) $\Phi_0(z)$ is bounded above and below by positive constants $c_1 \leq \Phi_0(z) \leq c_2$.

(ii) $\Delta_0 \ln \Phi_0 \geq 0$ for all $z \in C - \bigcup_\nu D_\nu(a)$, the domain where the function $\Phi_0$ is defined.

(iii) $\Delta_0 \ln \Phi_0 \geq c_3\delta^{-2}$ when $(1 - 2a)\delta < |z - z_\nu| < (1 - a)\delta$.

Let $A_\nu$ denote the annulus $A_\nu = \{(1 - 2a)\delta < |z - z_\nu| < (1 - a)\delta\}$, and set $A = \bigcup_\nu A_\nu$. The properties (2) and (3) of $\Phi_0$ may be summarized as $\Delta_0 \ln \Phi_0 \geq c_3\delta^{-2} \chi_A$, where $\chi_A$ is the characteristic function of $A$. \hfill $\square$

Suppose that $\alpha$ is a nonnegative real constant. We apply Proposition 3.5 with $\Phi(z) = \Phi_0(z)e^{\alpha|z|^2}$. If $u \in C^\infty_0(R^2 - \bigcup_\nu D_\nu(a))$, assume that $D$ is a bounded domain containing the support of $u$ and $A \subset D \subset R^2 - \bigcup_\nu D_\nu(a)$. A calculation gives

$$\int_D |\partial u|^2 \Phi_0(z)e^{\alpha|z|^2} \geq c_4 \alpha \int_D |u|^2 \Phi_0 e^{\alpha|z|^2} + c_5 \delta^{-2} \int_A |u|^2 \Phi_0 e^{\alpha|z|^2}.$$
The boundedness, property (1) of $\Phi_0$, then yields

$$
\int_D |\partial u|^2 e^{\alpha|z|^2} \geq c_6 \alpha \int_D |u|^2 e^{\alpha|z|^2} + c_7 \delta^{-2} \int_A |u|^2 e^{\alpha|z|^2}.
$$

Let $B(X)$ be the set of blocks of $\Lambda_X$ and let $b(X) = |B(X)|$. If $\phi \in Q_X$ then $\phi$ is constant on the blocks of $\Lambda_X$.

$P_X = \{ \phi \in M \mid \Lambda_\phi = \Lambda_X \}$, $Q_X = \{ \phi \in M \mid \Lambda_\phi \geq \Lambda_X \}$. (24)

If $\Lambda_\phi \geq \Lambda_X$ then $\Lambda_\phi = \Lambda_Y$ for some $Y \geq X$ so that

$$Q_X = \bigcup_{Y \geq X} P_Y.$$

Thus by Möbius inversion

$$|P_Y| = \sum_{X \geq Y} \mu(Y, X) |Q_X|.$$

Thus there is a bijection from $Q_X$ to $W^{B(X)}$. In particular $|Q_X| = w^{b(X)}$.

Next note that $b(X) = \dim X$. We see this by choosing a basis for $X$ consisting of vectors $v^k$ defined by

$$v^k_i = \begin{cases} 1 & \text{if } i \in \Lambda_k, \\ 0 & \text{otherwise.} \end{cases}$$

Lemma 6.2. Let $A$ be an arrangement. Then

$$\chi(A, t) = \sum_{B \subseteq A} (-1)^{|B|} t^{\dim T(B)}.$$

In order to compute $R''$ recall the definition of $S(X, Y)$ from Lemma 3.1. Since $H \in B$, $A_H \subseteq B$. Thus if $T(B) = Y$ then $B \in S(H, Y)$. Let $L'' = L(A'')$. Then

$$R'' = \sum_{H \subseteq \subseteq A} (-1)^{|B|} t^{\dim T(B)}$$

$$= \sum_{Y \in L''} \sum_{B \in S(H, Y)} (-1)^{|B|} t^{\dim Y}$$

$$= -\sum_{Y \in L''} \sum_{B \in S(H, Y)} (-1)^{|B - A_H|} t^{\dim Y}$$

$$= -\sum_{Y \in L''} \mu(H, Y) t^{\dim Y}$$

$$= -\chi(A'', t).$$

(25)
Corollary 6.3. Let \((A, A', A'')\) be a triple of arrangements. Then
\[
\pi(A, t) = \pi(A', t) + t\pi(A'', t).
\]

Definition 6.2. Let \((A, A', A'')\) be a triple with respect to the hyperplane \(H \in A\). Call \(H\) a separator if \(T(A) \not\in L(A')\).

Corollary 6.4. Let \((A, A', A'')\) be a triple with respect to \(H \in A\).

(i) If \(H\) is a separator then
\[
\mu(A) = -\mu(A'')
\]
and hence
\[
|\mu(A)| = |\mu(A'')|.
\]

(ii) If \(H\) is not a separator then
\[
\mu(A) = \mu(A') - \mu(A'')
\]
and
\[
|\mu(A)| = |\mu(A')| + |\mu(A'')|.
\]

Proof. It follows from Theorem 5.1 that \(\pi(A, t)\) has leading term
\[
(-1)^{r(A)} \mu(A) t^{r(A)}.
\]
The conclusion follows by comparing coefficients of the leading terms on both sides of the equation in Corollary 6.3. If \(H\) is a separator then \(r(A') < r(A)\) and there is no contribution from \(\pi(A', t)\).

The Poincaré polynomial of an arrangement will appear repeatedly in these notes. It will be shown to equal the Poincaré polynomial of the graded algebras which we are going to associate with \(A\). It is also the Poincaré polynomial of the complement \(M(A)\) for a complex arrangement. Here we prove that the Poincaré polynomial is the chamber counting function for a real arrangement. The complement \(M(A)\) is a disjoint union of chambers
\[
M(A) = \bigcup_{C \in \text{Cham}(A)} C.
\]
The number of chambers is determined by the Poincaré polynomial as follows.

Theorem 6.5. Let \(A_R\) be a real arrangement. Then
\[
|\text{Cham}(A_R)| = \pi(A_R, 1).
\]

Proof. We check the properties required in Corollary 6.4: (i) follows from \(\pi(\Phi_t, t) = 1\), and (ii) is a consequence of Corollary 3.4.
Figure 1: $Q(A_1) = xyz(x-z)(y+z)$

Figure 2: $Q(A_2) = xyz(x+y+z)(x+y-z)(x-y+z)(x-y-z)$
Theorem 6.6. Let $\phi$ be a protocol for a random pair $(X,Y)$. If one of $\sigma(x',y)$ and $\sigma(x,y')$ is a prefix of the other and $(x,y) \in S_{X,Y}$, then

$$\langle \sigma_j(x',y) \rangle_{j=1}^\infty = \langle \sigma_j(x,y) \rangle_{j=1}^\infty = \langle \sigma_j(x,y') \rangle_{j=1}^\infty.$$  

Proof. We show by induction on $i$ that

$$\langle \sigma_j(x',y) \rangle_{j=1}^i = \langle \sigma_j(x,y) \rangle_{j=1}^i = \langle \sigma_j(x,y') \rangle_{j=1}^i.$$  

The induction hypothesis holds vacuously for $i = 0$. Assume it holds for $i - 1$, in particular $[\sigma_j(x',y)]_{j=1}^{i-1} = [\sigma_j(x,y')]_{j=1}^{i-1}$. Then one of $[\sigma_j(x',y)]_{j=1}^{i}$ and $[\sigma_j(x,y')]_{j=1}^{i}$ is a prefix of the other which implies that one of $\sigma(x',y)$ and $\sigma(x,y')$ is a prefix of the other. If the $i$th message is transmitted by $P_X$ then, by the separate-transmissions property and the induction hypothesis, $\sigma_i(x,y) = \sigma_i(x,y')$, hence one of $\sigma_i(x,y)$ and $\sigma_i(x',y')$ is a prefix of the other. By the implicit-termination property, neither $\sigma_i(x,y)$ nor $\sigma_i(x',y')$ can be a proper prefix of the other, hence they must be the same and $\sigma_i(x',y) = \sigma_i(x,y) = \sigma_i(x,y')$. If the $i$th message is transmitted by $P_Y$ then, symmetrically, $\sigma_i(x,y) = \sigma_i(x',y')$ by the induction hypothesis and the separate-transmissions property, and, then, $\sigma_i(x,y) = \sigma_i(x,y')$ by the implicit-termination property, proving the induction step. \hfill $\Box$

If $\phi$ is a protocol for $(X,Y)$, and $(x,y), (x',y)$ are distinct inputs in $S_{X,Y}$, then, by the correct-decision property, $\langle \sigma_j(x,y)\rangle_{j=1}^\infty \neq \langle \sigma_j(x',y')\rangle_{j=1}^\infty$.

Equation (25) defined $P_Y$’s ambiguity set $S_{X|Y}(y)$ to be the set of possible $X$ values when $Y = y$. The last corollary implies that for all $y \in S_Y$, the multiset\(^1\) of codewords $\{\sigma(x,y) : x \in S_{X|Y}(y)\}$ is prefix free.

7 One-Way Complexity

$\tilde{C}_1(X|Y)$, the one-way complexity of a random pair $(X,Y)$, is the number of bits $P_X$ must transmit in the worst case when $P_Y$ is not permitted to transmit any feedback messages. Starting with $S_{X,Y}$, the support set of $(X,Y)$, we define $G(X|Y)$, the characteristic hypergraph of $(X,Y)$, and show that

$$\tilde{C}_1(X|Y) = \lceil \log \chi(G(X|Y)) \rceil.$$  

Let $(X,Y)$ be a random pair. For each $y$ in $S_Y$, the support set of $Y$, Equation (25) defined $S_{X|Y}(y)$ to be the set of possible $x$ values when $Y = y$. The characteristic hypergraph $G(X|Y)$ of $(X,Y)$ has $S_X$ as its vertex set and the hyperedge $S_{X|Y}(y)$ for each $y \in S_Y$.

We can now prove a continuity theorem.

\(^1\)A multiset allows multiplicity of elements. Hence, $\{0,01,01\}$ is prefix free as a set, but not as a multiset.
Theorem 7.1. Let $\Omega \subset \mathbb{R}^n$ be an open set, let $u \in BV(\Omega; \mathbb{R}^m)$, and let

$$T^u_x = \left\{ y \in \mathbb{R}^m : y = \bar{u}(x) + \frac{Du}{|Du|}(x), z \right\}$$

for every $x \in \Omega \setminus S_u$. Let $f: \mathbb{R}^m \to \mathbb{R}^k$ be a Lipschitz continuous function such that $f(0) = 0$, and let $v = f(u): \Omega \to \mathbb{R}^k$. Then $v \in BV(\Omega; \mathbb{R}^k)$ and

$$Jv = \left( f(u^+) - f(u^-) \right) \cdot \nu_u \cdot \mathcal{H}_{n-1}|_{S_u}.$$

In addition, for $Du$-almost every $x \in \Omega$ the restriction of the function $f$ to $T^u_x$ is differentiable at $\bar{u}(x)$ and

$$\bar{D}v = \nabla (f|_{T^u_x})(\bar{u}) \frac{\bar{D}u}{|D\bar{u}|} \cdot |\bar{D}u|.$$

Before proving the theorem, we state without proof three elementary remarks which will be useful in the sequel.

Remark 7.1. Let $\omega: [0, +\infty[ \to [0, +\infty[$ be a continuous function such that $\omega(t) \to 0$ as $t \to 0$. Then

$$\lim_{h \to 0^+} \frac{g(\omega(h))}{h} = L \Leftrightarrow \lim_{h \to 0^+} \frac{g(h)}{h} = L$$

for any function $g: [0, +\infty[ \to \mathbb{R}$.

Remark 7.2. Let $g: \mathbb{R}^n \to \mathbb{R}$ be a Lipschitz continuous function and assume that

$$L(z) = \lim_{h \to 0^+} \frac{g(hz) - g(0)}{h}$$

exists for every $z \in \mathbb{Q}^n$ and that $L$ is a linear function of $z$. Then $g$ is differentiable at 0.

Remark 7.3. Let $A: \mathbb{R}^n \to \mathbb{R}^m$ be a linear function, and let $f: \mathbb{R}^m \to \mathbb{R}$ be a function. Then the restriction of $f$ to the range of $A$ is differentiable at 0 if and only if $f(A): \mathbb{R}^n \to \mathbb{R}$ is differentiable at 0 and

$$\nabla (f|_{\text{Im}(A)})(0) A = \nabla (f(A))(0).$$

Proof. We begin by showing that $v \in BV(\Omega; \mathbb{R}^k)$ and

$$|Dv| (B) \leq K |Du| (B) \quad \forall B \in \mathcal{B}(\Omega),$$

where $K > 0$ is the Lipschitz constant of $f$. By (13) and by the approximation result quoted in §3, it is possible to find a sequence $(u_h) \subset C^1(\Omega; \mathbb{R}^m)$ converging to $u$ in $L^2(\Omega; \mathbb{R}^m)$ and such that

$$\lim_{h \to +\infty} \int_{\Omega} |\nabla u_h| \, dx = |Du| (\Omega).$$
The functions $v_h = f(u_h)$ are locally Lipschitz continuous in $\Omega$, and the definition of differential implies that $|\nabla v_h| \leq K |\nabla u_h|$ almost everywhere in $\Omega$. The lower semicontinuity of the total variation and (13) yield

$$|Dv| (\Omega) \leq \liminf_{h \to +\infty} |Dv_h| (\Omega) = \liminf_{h \to +\infty} \int_\Omega |\nabla v_h| \, dx \leq K \liminf_{h \to +\infty} \int_\Omega |\nabla u_h| \, dx = K |Du| (\Omega).$$

(30)

Since $f(0) = 0$, we have also

$$\int_\Omega |v| \, dx \leq K \int_\Omega |u| \, dx;$$

therefore $u \in BV(\Omega; \mathbb{R}^k)$. Repeating the same argument for every open set $A \subset \Omega$, we get (29) for every $B \in B(\Omega)$, because $|Dv|, |Du|$ are Radon measures.

To prove Lemma 6.1, first we observe that $S_v \subset S_u$, $\tilde{v}(x) = f(\tilde{u}(x)) \forall x \in \Omega \setminus S_u$. (31)

In fact, for every $\varepsilon > 0$ we have

$$\{ y \in B_\rho(x) : |v(y) - f(\tilde{u}(x))| > \varepsilon \} \subset \{ y \in B_\rho(x) : |u(y) - \tilde{u}(x)| > \varepsilon/K \},$$

hence

$$\lim_{\rho \to 0^+} \frac{\rho^n}{\rho^n} \{ y \in B_\rho(x) : |v(y) - f(\tilde{u}(x))| > \varepsilon \} = 0$$

whenever $x \in \Omega \setminus S_u$. By a similar argument, if $x \in S_u$ is a point such that there exists a triplet $(u^+, u^-, \nu_u)$ satisfying (14), (15), then

$$(u^+(x) - u^-(x)) \otimes \nu_v = (f(u^+(x)) - f(u^-(x))) \otimes \nu_u \quad \text{if} \quad x \in S_v$$

and $f(u^-(x)) = f(u^+(x))$ if $x \in S_u \setminus S_v$. Hence, by (1.8) we get

$$J_v(B) = \int_{B \cap S_v} (u^+ - u^-) \otimes \nu_v \, dH_{n-1} = \int_{B \cap S_v} (f(u^+) - f(u^-)) \otimes \nu_u \, dH_{n-1}$$

$$= \int_{B \cap S_u} (f(u^+) - f(u^-)) \otimes \nu_u \, dH_{n-1}$$

and Lemma 6.1 is proved. $\square$

To prove (31), it is not restrictive to assume that $k = 1$. Moreover, to simplify our notation, from now on we shall assume that $\Omega = \mathbb{R}^n$. The proof of (31) is divided into two steps. In the first step we prove the statement in the one-dimensional case ($n = 1$), using Theorem 5.2. In the second step we achieve the general result using Theorem 7.1.
Step 1

Assume that \( n = 1 \). Since \( S_u \) is at most countable, (7) yields that \( \tilde{D}v \mid (S_u \setminus S_v) = 0 \), so that (19) and (21) imply that \( Dv = \tilde{D}v + Jv \) is the Radon-Nikodým decomposition of \( Dv \) in absolutely continuous and singular part with respect to \( \tilde{D}u \). By Theorem 5.2, we have

\[
\frac{\tilde{D}v}{\tilde{D}u}(t) = \lim_{s \to t^+} \frac{Dv([t, s])}{\tilde{D}u([t, s])}, \quad \frac{\tilde{D}u}{\tilde{D}u}(t) = \lim_{s \to t^+} \frac{Du([t, s])}{\tilde{D}u([t, s])}
\]

\( \tilde{D}u \)-almost everywhere in \( \mathbb{R} \). It is well known (see, for instance, [12, 2.5.16]) that every one-dimensional function of bounded variation \( w \) has a unique left continuous representative, i.e., a function \( \hat{w} \) such that \( \hat{w} = w \) almost everywhere and \( \lim_{s \to t^-} \hat{w}(s) = \hat{w}(t) \) for every \( t \in \mathbb{R} \). These conditions imply

\[
\hat{u}(t) = Du([-\infty, t]), \quad \hat{v}(t) = Dv([-\infty, t]) \quad \forall t \in \mathbb{R}
\]

and

\[
\hat{v}(t) = f(\hat{u}(t)) \quad \forall t \in \mathbb{R}.
\]

Let \( t \in \mathbb{R} \) be such that \( \tilde{D}u \mid ([t, s]) > 0 \) for every \( s > t \) and assume that the limits in (22) exist. By (23) and (24) we get

\[
\frac{\hat{v}(s) - \hat{v}(t)}{\tilde{D}u \mid ([t, s])} = \frac{f(\hat{u}(s)) - f(\hat{u}(t))}{\tilde{D}u \mid ([t, s])} = f(\hat{u}(s)) - f(\hat{u}(t)) + \frac{\tilde{D}u \mid ([t, s])}{\tilde{D}u \mid ([t, s])} \left( \frac{\tilde{D}u \mid ([t, s])}{\tilde{D}u \mid ([t, s])} \right) - \frac{f(\hat{u}(t))}{\tilde{D}u \mid ([t, s])}
\]

for every \( s > t \). Using the Lipschitz condition on \( f \) we find

\[
\left| \frac{\hat{v}(s) - \hat{v}(t)}{\tilde{D}u \mid ([t, s])} - \frac{\tilde{D}u \mid ([t, s])}{\tilde{D}u \mid ([t, s])} \right| \leq K \left| \frac{\hat{u}(s) - \hat{u}(t)}{\tilde{D}u \mid ([t, s])} - \frac{\tilde{D}u \mid ([t, s])}{\tilde{D}u \mid ([t, s])} \right|.
\]
By (29), the function \( s \to \left| \mathcal{D}u \right| ([t, s]) \) is continuous and converges to 0 as \( s \downarrow t \).
Therefore Remark 7.1 and the previous inequality imply

\[
\frac{\mathcal{D}v}{\mathcal{D}u}(t) = \lim_{h \to 0^+} \frac{f(\tilde{u}(t) + h \mathcal{D}u(t)) - f(\tilde{u}(t))}{h} \quad \left| \mathcal{D}u \right| \text{-a.e. in } \mathbb{R}.
\]

By (22), \( \tilde{u}(x) = \tilde{u}(x) \) for every \( x \in \mathbb{R} \setminus S_u \); moreover, applying the same argument to the functions \( u'(t) = u(-t) \), \( v'(t) = f(u'(t)) = v(-t) \), we get

\[
\frac{\mathcal{D}v}{\mathcal{D}u}(t) = \lim_{h \to 0} \frac{f(\tilde{u}(t) + h \mathcal{D}u(t)) - f(\tilde{u}(t))}{h} \quad \left| \mathcal{D}u \right| \text{-a.e. in } \mathbb{R}
\]

and our statement is proved.

**Step 2**

Let us consider now the general case \( n > 1 \). Let \( \nu \in \mathbb{R}^n \) be such that \( |\nu| = 1 \), and let \( \pi_\nu = \{ y \in \mathbb{R}^n : \langle y, \nu \rangle = 0 \} \). In the following, we shall identify \( \mathbb{R}^n \) with \( \pi_\nu \times \mathbb{R} \), and we shall denote by \( y \) the variable ranging in \( \pi_\nu \) and by \( t \) the variable ranging in \( \mathbb{R} \). By the just proven one-dimensional result, and by Theorem 3.3, we get

\[
\lim_{h \to 0} \frac{f(\tilde{u}(y + t\nu) + h \mathcal{D}u_y(t)) - f(\tilde{u}(y + t\nu))}{h} = \frac{\mathcal{D}v_y}{\mathcal{D}u_y}(t) \quad \left| \mathcal{D}u_y \right| \text{-a.e. in } \mathbb{R}
\]

for \( H_{n-1} \)-almost every \( y \in \pi_\nu \). We claim that

\[
\frac{\langle \mathcal{D}u_y, \nu \rangle}{\langle \mathcal{D}u, \nu \rangle}(y + t\nu) = \frac{\mathcal{D}u_y}{\mathcal{D}u}(t) \quad \left| \mathcal{D}u_y \right| \text{-a.e. in } \mathbb{R} \quad (34)
\]

for \( H_{n-1} \)-almost every \( y \in \pi_\nu \). In fact, by (16) and (18) we get

\[
\int_{\pi_\nu} \frac{\mathcal{D}u_y}{\mathcal{D}u}(t) \left| \mathcal{D}u_y \right| \ dH_{n-1}(y) = \int_{\pi_\nu} \mathcal{D}u_y \ dH_{n-1}(y)
\]

\[
= \langle \mathcal{D}u, \nu \rangle = \frac{\langle \mathcal{D}u_y, \nu \rangle}{\langle \mathcal{D}u, \nu \rangle} \left| \mathcal{D}u_y \right| \quad \text{by (16) and (18)}
\]

\[
= \int_{\pi_\nu} \frac{\mathcal{D}u_y}{\mathcal{D}u}(y + t\nu) \left| \mathcal{D}u_y \right| \ dH_{n-1}(y)
\]
and (24) follows from (13). By the same argument it is possible to prove that

\[
\begin{align*}
\frac{\langle \tilde{D}v, \nu \rangle}{\langle \tilde{Du}, \nu \rangle}(y + tv) &= \frac{\tilde{D}v_y}{\tilde{D}u_y}(t) \quad \tilde{D}u_y \text{ -a.e. in } \mathbf{R} \\
\end{align*}
\]

for $\mathcal{H}_{n-1}$-almost every $y \in \pi_\nu$. By (24) and (25) we get

\[
\lim_{h \to 0} \frac{f(\tilde{v}(y + tv) + h \langle \tilde{D}u, \nu \rangle(y + tv)) - f(\tilde{v}(y + tv))}{h} = \frac{\langle \tilde{D}v, \nu \rangle}{\langle \tilde{D}u, \nu \rangle}(y + tv)
\]

for $\mathcal{H}_{n-1}$-almost every $y \in \pi_\nu$, and using again (14), (15) we get

\[
\lim_{h \to 0} \frac{f(\tilde{v}(x) + h \langle \tilde{D}u, \nu \rangle(x)) - f(\tilde{v}(x))}{h} = \frac{\langle \tilde{D}v, \nu \rangle}{\langle \tilde{D}u, \nu \rangle}(x)
\]

$\langle \tilde{D}u, \nu \rangle$-a.e. in $\mathbf{R}^n$.

Since the function $\frac{\langle \tilde{D}u, \nu \rangle}{\tilde{D}u}$ is strictly positive $\langle \tilde{D}u, \nu \rangle$-almost everywhere, we obtain also

\[
\lim_{h \to 0} \frac{f(\tilde{v}(x) + h \langle \tilde{D}u, \nu \rangle(x) \langle \tilde{D}v, \nu \rangle(x)) - f(\tilde{v}(x))}{h} = \frac{\langle \tilde{D}u, \nu \rangle}{\langle \tilde{D}u, \nu \rangle}(x)
\]

$\langle \tilde{D}u, \nu \rangle$-almost everywhere in $\mathbf{R}^n$.

Finally, since

\[
\begin{align*}
\frac{\langle \tilde{D}u, \nu \rangle}{\tilde{D}u} \frac{\langle \tilde{D}u, \nu \rangle}{\langle \tilde{D}u, \nu \rangle} &= \langle \tilde{D}u, \nu \rangle \frac{\tilde{D}u}{\tilde{D}u} \frac{\tilde{D}u}{\langle \tilde{D}u, \nu \rangle} \quad \tilde{D}u \text{ -a.e. in } \mathbf{R}^n \\
\frac{\langle \tilde{D}v, \nu \rangle}{\tilde{D}u} \frac{\langle \tilde{D}v, \nu \rangle}{\langle \tilde{D}v, \nu \rangle} &= \langle \tilde{D}v, \nu \rangle \frac{\tilde{D}v}{\tilde{D}u} \frac{\tilde{D}v}{\langle \tilde{D}v, \nu \rangle} \quad \tilde{D}u \text{ -a.e. in } \mathbf{R}^n
\end{align*}
\]
and since both sides of (33) are zero \( |\tilde{D}u|\)-almost everywhere on \( |(\tilde{D}u, \nu)|\)-negligible sets, we conclude that

\[
\lim_{h \to 0} f \left( \tilde{u}(x) + h \left( \frac{\tilde{D}u}{\tilde{D}u}(x), \nu \right) \right) - \tilde{f}(\tilde{u}(x)) h = \left( \frac{\tilde{D}v}{\tilde{D}u}(x), \nu \right),
\]

\( |\tilde{D}u|\)-a.e. in \( \mathbb{R}^n \). Since \( \nu \) is arbitrary, by Remarks 7.2 and 7.3 the restriction of \( f \) to the affine space \( T_xu \) is differentiable at \( \tilde{u}(x) \) for \( |\tilde{D}u| \)-almost every \( x \in \mathbb{R}^n \) and (26) holds.

It follows from (13), (14), and (15) that

\[
D(t_1, \ldots, t_n) = \sum_{I \subseteq [n]} (-1)^{|I|-1} |I| |I| \prod_{i \in I} t_i \prod_{j \in I} (D_j + \lambda_j t_j) \det A^{(\lambda)}(I|T). \tag{36}
\]

Let \( t_i = \hat{x}_i, i = 1, \ldots, n \). Lemma 1 leads to

\[
D(\hat{x}_1, \ldots, \hat{x}_n) = \prod_{i \in [n]} \hat{x}_i \sum_{I \subseteq [n]} (-1)^{|I|-1} |I| \per A^{(\lambda)}(I|I) \det A^{(\lambda)}(T|T). \tag{37}
\]

By (3), (13), and (37), we have the following result:

**Theorem 7.2.**

\[
H_c = \frac{1}{2n} \sum_{l=1}^{n} l(-1)^{|l|-1} A^{(\lambda)}_l,
\]

where

\[
A^{(\lambda)}_l = \sum_{I \subseteq [n]} \per A^{(\lambda)}(I|I) \det A^{(\lambda)}(T|T), |I| = l. \tag{39}
\]

It is worth noting that \( A^{(\lambda)}_l \) of (39) is similar to the coefficients \( b_l \) of the characteristic polynomial of (10). It is well known in graph theory that the coefficients \( b_l \) can be expressed as a sum over certain subgraphs. It is interesting to see whether \( A_l, \lambda = 0 \), structural properties of a graph.

We may call (38) a parametric representation of \( H_c \). In computation, the parameter \( \lambda \) plays very important roles. The choice of the parameter usually depends on the properties of the given graph. For a complete graph \( K_n \), let \( \lambda_i = 1, i = 1, \ldots, n \). It follows from (39) that

\[
A^{(1)}_l = \begin{cases} 
 n!, & \text{if } l = 1 \\
 0, & \text{otherwise}.
\end{cases} \tag{40}
\]

By (38)

\[
H_c = \frac{1}{2} (n-1)i. \tag{41}
\]
For a complete bipartite graph \( K_{n_1,n_2} \), let \( \lambda_i = 0, \ i = 1, \ldots, n \). By (39),

\[
A_l = \begin{cases} 
eg n_1!n_2!\delta_{n_1,n_2}, & \text{if } l = 2 \\ 0, & \text{otherwise} \end{cases}.
\] (42)

Theorem 7.2 leads to

\[
H_c = \frac{1}{n_1 + n_2} n_1!n_2!\delta_{n_1,n_2}.
\] (43)

Now, we consider an asymmetrical approach. Theorem 3.3 leads to

\[
\det K(t = 1, t_1, \ldots, t_n; l|l) = \sum_{I \subseteq n\setminus\{l\}} (-1)^{|I|} \prod_{i \in I} t_i \prod_{j \in I} (D_j + \lambda_j t_j) \det A^{(\lambda)}(T \cup \{l\}|T \cup \{l\}).
\] (44)

By (3) and (16) we have the following asymmetrical result:

**Theorem 7.3.**

\[
H_c = \frac{1}{2} \sum_{I \subseteq n\setminus\{l\}} (-1)^{|I|} \text{per} A^{(\lambda)}(I|I) \det A^{(\lambda)}(T \cup \{l\}|T \cup \{l\})
\] (45)

which reduces to Goulden–Jackson’s formula when \( \lambda_i = 0, i = 1, \ldots, n \) [9].

## 8 Various font features of the amsmath package

### 8.1 Bold versions of special symbols

In the amsmath package \texttt{\textbackslash boldsymbol} is used for getting individual bold math symbols and bold Greek letters—everything in math except for letters of the Latin alphabet, where you’d use \texttt{\textbackslash mathbf}. For example,

\begin{verbatim}
A \infty + \pi A_0 \ni \im
\textbf{A}\_\{\textbf{\textbackslash infty}\} \textbf{\textbackslash pi}
\textbf{A}\_\{\textbf{\textbackslash infty}\} \textbf{\textbackslash pi}
\end{verbatim}

looks like this:

\[
A_\infty + \pi A_0 \sim A_\infty + \pi A_0
\]

### 8.2 “Poor man’s bold”

If a bold version of a particular symbol doesn’t exist in the available fonts, then \texttt{\textbackslash boldsymbol} can’t be used to make that symbol bold. At the present time, this means that \texttt{\textbackslash boldsymbol} can’t be used with symbols from the \texttt{\textbackslash msam} and \texttt{\textbackslash msbm} fonts, among others. In some cases, poor man’s bold (\texttt{\textbackslash pmb}) can be used instead of \texttt{\textbackslash boldsymbol}:

\[
\frac{\partial x}{\partial y} \bigg| \frac{\partial y}{\partial z}
\]
\[ \frac{\partial x}{\partial y} \pmb{\bigg\vert} \frac{\partial y}{\partial z} \]

So-called “large operator” symbols such as $\sum$ and $\prod$ require an additional command, \texttt{\textbackslash mathop}, to produce proper spacing and limits when \texttt{\textbackslash pmb} is used. For further details see \textit{The TEXbook}.

\[
\sum_{i<B} \prod_{\kappa} \kappa F(r_i) \quad \sum_{i<B} \prod_{\kappa} \kappa(r_i)
\]

9 Compound symbols and other features

9.1 Multiple integral signs

\texttt{\textbackslash iiint}, \texttt{\textbackslash iiiint}, and \texttt{\textbackslash iiiiint} give multiple integral signs with the spacing between them nicely adjusted, in both text and display style. \texttt{\textbackslash idotsint} gives two integral signs with dots between them.

\[
\begin{align*}
\iiint_A f(x, y) \, dx \, dy & \quad \iiint_A f(x, y, z) \, dx \, dy \, dz \\ 
\iiint_A f(w, x, y, z) \, dw \, dx \, dy \, dz & \quad \cdots \int_A f(x_1, \ldots, x_k)
\end{align*}
\]

9.2 Over and under arrows

Some extra over and under arrow operations are provided in the \texttt{amsmath} package. (Basic \LaTeX provides \texttt{\textbackslash overrightarrow} and \texttt{\textbackslash overleftarrow}).

\[
\begin{align*}
\overrightarrow{\psi_3(t) E_t h} & = \psi_3(t) E_t h \\
\overleftarrow{\psi_3(t) E_t h} & = \psi_3(t) E_t h
\end{align*}
\]
Sample paper for the amsmath package

\begin{align*}
=\underleftarrow{\psi_\delta(t) E_t h} \\
\overleftrightarrow{\psi_\delta(t) E_t h} & =\underleftrightarrow{\psi_\delta(t) E_t h}
\end{align*}

These all scale properly in subscript sizes:

\[
\int_{\overrightarrow{AB}} ax \, dx
\]

9.3 Dots

Normally you need only type \dots for ellipsis dots in a math formula. The main exception is when the dots fall at the end of the formula; then you need to specify one of \dotsc (series dots, after a comma), \dotsb (binary dots, for binary relations or operators), \dotsm (multiplication dots), or \dotsi (dots after an integral). For example, the input

Then we have the series $A_1,A_2,\dotsc$, the regional sum $A_1+A_2+\dotsb$, the orthogonal product $A_1A_2\dotsm$, and the infinite integral

\[
\int_{A_1}\int_{A_2}\dotsi\]

produces

Then we have the series $A_1,A_2,\ldots$, the regional sum $A_1+A_2+\cdots$, the orthogonal product $A_1A_2\cdots$, and the infinite integral

\[
\int_{A_1}\int_{A_2}\cdots
\]

9.4 Accents in math

Double accents:

\[
\Hat{\Hat{H}} \quad \Check{\Check{C}} \quad \Tilde{\Tilde{T}} \quad \Acute{\Acute{A}} \quad \Grave{\Grave{G}} \quad \Dot{\Dot{D}} \quad \Ddot{\Ddot{D}} \quad \Breve{\Breve{B}} \quad \Bar{\Bar{B}} \quad \Vec{\Vec{V}}
\]

This double accent operation is complicated and tends to slow down the processing of a \LaTeX file.
9.5 Dot accents
\dddot and \ddddot are available to produce triple and quadruple dot accents in addition to the \dot and \ddot accents already available in \LaTeX:

\[ \dddot{Q} \quad \ddddot{R} \]

9.6 Roots
In the \amsmath package \leftroot and \uproot allow you to adjust the position of the root index of a radical:

\[ \sqrt[\leftroot{-2}\uproot{2}]\beta \{k} \]
gives good positioning of the $\beta$:

\[ \sqrt[2]{k} \]

9.7 Boxed formulas
The command \boxed puts a box around its argument, like \fbox except that the contents are in math mode:

\[ \boxed{W_t-F \subseteq V(P_i) \subseteq W_t} \]

9.8 Extensible arrows
\xleftarrow and \xrightarrow produce arrows that extend automatically to accommodate unusually wide subscripts or superscripts. The text of the subscript or superscript are given as an optional resp. mandatory argument: Example:

\[ 0 \xleftarrow[\zeta]{\alpha} \ F \times \triangle [n-1] \xrightarrow{\partial_0 b} E^\partial_0 b \]

9.9 \overset, \underset, and \sideset
Examples:

\[ \overset{\ast}{X} \quad X \underset{b}{\ast} \quad \overset{\ast}{X} \]

\[ \overset{\ast}{\{X}\quad \underset{\ast}{\{X}\quad \overset{\ast}{\{X} \\\underset{b}{\{X} \\quad \overset{\ast}{a}\{\underset{b}{\{X} \}\} \]
The command \text is for words or phrases in a display:

\text{if and only if} \quad y'_k = \delta_k y_{\tau(k)}

\textbf{y} = \textbf{y}' \text{ if and only if } y'_k = \delta_k y_{\tau(k)}

9.11 Operator names

The more common math functions such as log, sin, and lim have predefined control sequences: \texttt{\log}, \texttt{\sin}, \texttt{\lim}. The \texttt{amsmath} package provides \texttt{\DeclareMathOperator} and \texttt{\DeclareMathOperator*} for producing new function names that will have the same typographical treatment. Examples:

$$\|f\|_{\infty} = \esssup_{x \in \mathbb{R}^n} |f(x)|$$

9.11 Operator names

The more common math functions such as log, sin, and lim have predefined control sequences: \texttt{\log}, \texttt{\sin}, \texttt{\lim}. The \texttt{amsmath} package provides \texttt{\DeclareMathOperator} and \texttt{\DeclareMathOperator*} for producing new function names that will have the same typographical treatment. Examples:

$$\|f\|_{\infty} = \esssup_{x \in \mathbb{R}^n} |f(x)|$$

The following special operator names are predefined in the \texttt{amsmath} package: \texttt{\varlimsup}, \texttt{\varliminf}, \texttt{\varinjlim}, and \texttt{\varprojlim}. Here’s what they
look like in use:

\[\lim_{n \to \infty} Q(u_n, u_n - u^\#) \leq 0\] (48)
\[\lim_{n \to \infty} \frac{|a_{n+1}|}{|a_n|} = 0\] (49)
\[\lim_{n \to \infty} (m_i^\lambda)^* \leq 0\] (50)
\[\lim_{p \in S(A)} A_p \leq 0\] (51)

\begin{align}
&\varlimsup_{n \to \infty} \mathcal{Q}(u_n, u_n - u^\#) \leq 0 \\
&\varliminf_{n \to \infty} \left| a_{n+1} \right| / \left| a_n \right| = 0 \\
&\varinjlim (m_i^\lambda \cdot)^* \leq 0 \\
&\varprojlim_{p \in S(A)} A_p \leq 0
\end{align}

9.12 \texttt{\textbackslash mod} and its relatives

The commands \texttt{\textbackslash mod} and \texttt{\textbackslash pod} are variants of \texttt{\textbackslash pmod} preferred by some authors; \texttt{\textbackslash mod} omits the parentheses, whereas \texttt{\textbackslash pod} omits the ‘mod’ and retains the parentheses. Examples:

\[x \equiv y + 1 \pmod{m^2}\] (52)
\[x \equiv y + 1 \mod{m^2}\] (53)
\[x \equiv y + 1 \pod{m^2}\] (54)

\begin{align}
x &\equiv y + 1 \pmod{m^2} \\
x &\equiv y + 1 \mod{m^2} \\
x &\equiv y + 1 \pod{m^2}
\end{align}

9.13 Fractions and related constructions

The usual notation for binomials is similar to the fraction concept, so it has a similar command \texttt{\textbackslash binom} with two arguments. Example:

\[\sum_{\gamma \in \Gamma_C} I_{\gamma} = 2^k - \binom{k}{1} 2^{k-1} + \binom{k}{2} 2^{k-2} + \cdots + (-1)^i \binom{k}{i} 2^{k-i} + \cdots + (-1)^k = (2 - 1)^k = 1\] (55)
\begin{equation}
\begin{split}
\sum_{\gamma \in \Gamma_C} I_\gamma &= 2^k - \binom{k}{1}2^{k-1} + \binom{k}{2}2^{k-2} \\
&\quad + \cdots + (-1)^l\binom{k}{l}2^{k-l} \\
&\quad + \cdots + (-1)^k \\
&= (2-1)^k = 1
\end{split}
\end{equation}

There are also abbreviations

\dfrac {\text{\textstyle\frac}} {\dbinom}
\tfrac {\text{\textstyle\frac}} {\tbinom}

for the commonly needed constructions

{\displaystyle\frac \ldots} {\displaystyle\binom \ldots}
{\textstyle\frac \ldots} {\textstyle\binom \ldots}

The generalized fraction command $\text{\textbf{\texttt{\textbackslash genfrac}}}$ provides full access to the six \TeX{} fraction primitives:

\begin{align}
\text{\textbf{\texttt{\textbackslash over}}:} \quad &\frac{n+1}{2} \quad \text{\textbf{\texttt{\textbackslash overwithdelims}}:} \quad \bigg(\frac{n+1}{2}\bigg) \\
\text{\textbf{\texttt{\textbackslash atop}}:} \quad &\frac{n+1}{2} \quad \text{\textbf{\texttt{\textbackslash atopwithdelims}}:} \quad \bigg(\frac{n+1}{2}\bigg) \\
\text{\textbf{\texttt{\textbackslash above}}:} \quad &\frac{n+1}{2} \quad \text{\textbf{\texttt{\textbackslash abovewithdelims}}:} \quad \bigg[\frac{n+1}{2}\bigg]
\end{align}

$\text{\textbf{\texttt{\textbackslash over}}} n+1 \frac{\text{\textbackslash over}}{2}
\text{\textbf{\texttt{\textbackslash above}}} n+1 \frac{\text{\textbackslash above}}{2}$

$\text{\textbf{\texttt{\textbackslash over}}} n+1 \frac{\text{\textbackslash over}}{2}
\text{\textbf{\texttt{\textbackslash above}}} n+1 \frac{\text{\textbackslash above}}{2}$

$\text{\textbf{\texttt{\textbackslash over}}} n+1 \frac{\text{\textbackslash over}}{2}
\text{\textbf{\texttt{\textbackslash above}}} n+1 \frac{\text{\textbackslash above}}{2}$

$\text{\textbf{\texttt{\textbackslash over}}} n+1 \frac{\text{\textbackslash over}}{2}
\text{\textbf{\texttt{\textbackslash above}}} n+1 \frac{\text{\textbackslash above}}{2}$

$\text{\textbf{\texttt{\textbackslash over}}} n+1 \frac{\text{\textbackslash over}}{2}
\text{\textbf{\texttt{\textbackslash above}}} n+1 \frac{\text{\textbackslash above}}{2}$

$\text{\textbf{\texttt{\textbackslash over}}} n+1 \frac{\text{\textbackslash over}}{2}
\text{\textbf{\texttt{\textbackslash above}}} n+1 \frac{\text{\textbackslash above}}{2}$
\section{Continued fractions}

The continued fraction
\begin{equation}
\cfrac{1}{\sqrt{2} + \cfrac{1}{\sqrt{2} + \cfrac{1}{\sqrt{2} + \cfrac{1}{\sqrt{2} + \cdots}}}}
\end{equation}

\begin{equation}
1 \quad \sqrt{2} + 1 \quad \sqrt{2} + 1 \quad \sqrt{2} + 1 \quad \sqrt{2} + \cdots
\end{equation}

can be obtained by typing
\begin{verbatim}
\cfrac{1}{\sqrt{2}+ \cfrac{1}{\sqrt{2}+ \cfrac{1}{\sqrt{2}+ \cfrac{1}{\sqrt{2}+\ldots}}}}
\end{verbatim}

Left or right placement of any of the numerators is accomplished by using \cfrac[l] or \cfrac[r] instead of \cfrac.

\section{Smash}

In \texttt{amsmath} there are optional arguments \texttt{t} and \texttt{b} for the plain \TeX \ command \texttt{\smash}, because sometimes it is advantageous to be able to ‘smash’ only the top or only the bottom of something while retaining the natural depth or height. In the formula
\begin{equation}
X_j = \frac{1}{\sqrt{\lambda_j}} X'_j \smash[b]
\end{equation}

has been used to limit the size of the radical symbol.

Without the use of \texttt{\smash[b]} the formula would have appeared thus:
\begin{equation}
X_j = \frac{1}{\sqrt{\lambda_j}} X'_j,
\end{equation}

with the radical extending to encompass the depth of the subscript \texttt{j}.

\section{The ‘cases’ environment}

‘Cases’ constructions like the following can be produced using the \texttt{cases} environment.
\begin{equation}
P_{r-j} = \begin{cases}
0 & \text{if } r-j \text{ is odd,} \\
r!(-1)^{(r-j)/2} & \text{if } r-j \text{ is even.}
\end{cases}
\end{equation}

\begin{verbatim}
\begin{equation}
P_{r-j} = \begin{cases}
0 & \text{if } r-j \text{ is odd,} \\
r!(-1)^{(r-j)/2} & \text{if } r-j \text{ is even.}
\end{cases}
\end{verbatim}

\end{cases}
\end{equation}

Notice the use of \text and the embedded math.

\section*{9.17 Matrix}

Here are samples of the matrix environments, \texttt{matrix}, \texttt{pmatrix}, \texttt{bmatrix}, \texttt{Bmatrix}, \texttt{vmatrix} and \texttt{Vmatrix}:

\begin{equation}
\begin{bmatrix}
\vartheta & \varrho \\
\varphi & \varpi \\
\end{bmatrix}
\end{equation}

(61)

To produce a small matrix suitable for use in text, use the \texttt{smallmatrix} environment.

\begin{math}
\bigl( \begin{smallmatrix}
a & b \\
c & d \\
\end{smallmatrix} \bigr)
\end{math}

To show the effect of the matrix on the surrounding lines of a paragraph, we put it here: \( \begin{pmatrix} a & b \\ c & d \end{pmatrix} \) and follow it with enough text to ensure that there will be at least one full line below the matrix.

\texttt{\textbackslash hdotsfor\{number\}} produces a row of dots in a matrix spanning the given
number of columns:

\[ W(\Phi) = \begin{Vmatrix} \frac{\varphi}{(\varphi_1, \varepsilon_1)} & 0 & \ldots & 0 \\
\frac{\varphi_{k_{n2}}}{(\varphi_2, \varepsilon_1)} & \frac{\varphi}{(\varphi_2, \varepsilon_2)} & \ldots & 0 \\
\frac{\varphi_{k_{n1}}}{(\varphi_n, \varepsilon_1)} & \frac{\varphi_{k_{n2}}}{(\varphi_n, \varepsilon_2)} & \ldots & \frac{\varphi}{(\varphi_n, \varepsilon_{n-1})} \\
\frac{\varphi_{k{n_{n-1}}}}{(\varphi_n, \varepsilon_{n-1})} & \frac{\varphi_{k_{n2}}}{(\varphi_n, \varepsilon_{n-1})} & \ldots & \frac{\varphi}{(\varphi_n, \varepsilon_n)} \end{Vmatrix} \]

The spacing of the dots can be varied through use of a square-bracket option, for example, \texttt{\hdotsfor[1.5]{3}}. The number in square brackets will be used as a multiplier; the normal value is 1.

9.18 The \texttt{\substack} command

The \texttt{\substack} command can be used to produce a multiline subscript or superscript: for example

\texttt{\sum_{\substack{0 \leq i \leq m \\ 0 < j < n}} P(i,j)}

produces a two-line subscript underneath the sum:

\[ \sum_{0 \leq i \leq m \atop 0 < j < n} P(i,j) \quad (62) \]

A slightly more generalized form is the \texttt{subarray} environment which allows you to specify that each line should be left-aligned instead of centered, as here:

\texttt{\sum_{\begin{subarray}{l} 0 \leq i \leq m \\
0 < j < n \end{subarray}} P(i,j)}

\[ \sum_{0 \leq i \leq m \atop 0 < j < n} P(i,j) \quad (63) \]
9.19 Big-g-g delimiters

Here are some big delimiters, first in \texttt{\normalsize}:

\[
\left( \mathbf{E}_y \int_0^{t_\varepsilon} L_{x,y^x(s)} \varphi(x) \, ds \right)
\]

and now in \texttt{\Large} size:

\[
\left( \mathbf{E}_y \int_0^{t_\varepsilon} L_{x,y^x(s)} \varphi(x) \, ds \right)
\]
A Examples of multiple-line equation structures

Note: Starting on this page, vertical rules are added at the margins so that the positioning of various display elements with respect to the margins can be seen more clearly.

A.1 Split

The split environment is not an independent environment but should be used inside something else such as equation or align.

If there is not enough room for it, the equation number for a split will be shifted to the previous line, when equation numbers are on the left; the number shifts down to the next line when numbers are on the right.

\[ f_{h,\varepsilon}(x,y) = \varepsilon E_{x,y} \int_0^{t_{\varepsilon}} L_{x,y_{\varepsilon}(\varepsilon u)} \varphi(x) \, du \]
\[ = h \int L_{x,z} \varphi(x) \rho_x(dz) \]
\[ + h \left[ \frac{1}{t_{\varepsilon}} \left( E_y \int_0^{t_{\varepsilon}} L_{x,y^x(s)} \varphi(x) \, ds - t_{\varepsilon} \int L_{x,z} \varphi(x) \rho_x(dz) \right) \right] \]
\[ + \frac{1}{t_{\varepsilon}} \left( E_y \int_0^{t_{\varepsilon}} L_{x,y_{\varepsilon}(\varepsilon s)} \varphi(x) \, ds - E_x,y \int_0^{t_{\varepsilon}} L_{x,y_{\varepsilon}(\varepsilon s)} \varphi(x) \, ds \right) \]
\[ = h \tilde{L}_x \varphi(x) + h \theta_{\varepsilon}(x,y), \]

Some text after to test the below-display spacing.

\begin{equation}
\begin{split}
f_{h,\varepsilon}(x,y) &= \varepsilon E_{x,y} \int_0^{t_{\varepsilon}} L_{x,y_{\varepsilon}(\varepsilon u)} \varphi(x) \, du \\
&= h \int L_{x,z} \varphi(x) \rho_x(dz) \\
&+ h \left[ \frac{1}{t_{\varepsilon}} \left( E_y \int_0^{t_{\varepsilon}} L_{x,y^x(s)} \varphi(x) \, ds - t_{\varepsilon} \int L_{x,z} \varphi(x) \rho_x(dz) \right) \right] \\
&+ \frac{1}{t_{\varepsilon}} \left( E_y \int_0^{t_{\varepsilon}} L_{x,y_{\varepsilon}(\varepsilon s)} \varphi(x) \, ds - E_x,y \int_0^{t_{\varepsilon}} L_{x,y_{\varepsilon}(\varepsilon s)} \varphi(x) \, ds \right) \\
&= h \tilde{L}_x \varphi(x) + h \theta_{\varepsilon}(x,y),
\end{split}
\end{equation}
Unnumbered version:

\[ f_{h,\varepsilon}(x, y) = \varepsilon \mathbf{E}_{x,y} \int_0^{t_\varepsilon} L_{x,y_\varepsilon(\varepsilon u)} \varphi(x) \, du \]
\[ = h \int L_{x,z} \varphi(x) \rho_x(dz) \]
\[ + \varepsilon \left[ \frac{1}{t_\varepsilon} \left( \mathbf{E}_y \int_0^{t_\varepsilon} L_{x,y^\varepsilon(s)} \varphi(x) \, ds - t_\varepsilon \int L_{x,z} \varphi(x) \rho_x(dz) \right) \right. \]
\[ \left. + \frac{1}{t_\varepsilon} \left( \mathbf{E}_y \int_0^{t_\varepsilon} L_{x,y^\varepsilon(s)} \varphi(x) \, ds - \mathbf{E}_{x,y} \int_0^{t_\varepsilon} L_{x,y_\varepsilon(\varepsilon s)} \varphi(x) \, ds \right) \right] \]
\[ = h \tilde{L}_x \varphi(x) + h \theta_\varepsilon(x, y), \]
If the option `centertags` is included in the options list of the `amsmath` package, the equation numbers for `split` environments will be centered vertically on the height of the `split`:

\[
|I_2| = \left| \int_0^T \psi(t) \left\{ u(a, t) - \int_{\gamma(t)}^a \frac{d\theta}{k(\theta, t)} \int_\theta^a c(\zeta) u_\zeta(\zeta, t) d\zeta \right\} dt \right| \\
\leq C_6 \left\| f \int_{\Omega} |\tilde{S}_{\alpha,-}^{-1,0} W_2(\Omega, \Gamma_1)| \left\| u \right\| \rightarrow W_2^3(\Omega; \Gamma_r, T) \right\|.
\] (65)

Some text after to test the below-display spacing.
Sample paper for the amsmath package

Use of split within align:

\begin{align}
|I_1| &= \left| \int_{\Omega} gR u \, d\Omega \right| \\
&\leq C_3 \left[ \int_{\Omega} \left( \int_{a}^{x} g(\xi, t) \, d\xi \right)^2 \, d\Omega \right]^{1/2} \\
&\quad \times \left[ \int_{\Omega} \left\{ u_x^2 + \frac{1}{k} \left( \int_{a}^{x} c u_t \, d\xi \right)^2 \right\} \, c \Omega \right]^{1/2} \\
&\leq C_4 \left| f \left| \wt{S}^{-1,0}_{a,-} W_2(\Omega, \Gamma_l) \right| \right| \left| u \right| \overset{\circ}{\rightarrow} W_2^{\wt{A}}(\Omega; \Gamma_r, T) \right|.
\end{align}

(66)

\begin{align}
|I_2| &= \left| \int_{0}^{T} \psi(t) \left\{ u(a, t) - \int_{\gamma(t)}^{a} \frac{d\theta}{k(\theta, t)} \int_{a}^{\theta} c(\xi) u_t(\xi, t) \, d\xi \right\} \, dt \right| \\
&\leq C_6 \left| f \int_{\Omega} \left| \wt{S}^{-1,0}_{a,-} W_2(\Omega, \Gamma_l) \right| \right| \left| u \right| \overset{\circ}{\rightarrow} W_2^{\wt{A}}(\Omega; \Gamma_r, T) \right|.
\end{align}

(67)

Some text after to test the below-display spacing.

\begin{align}
&= \left| \int_{\Omega} gR u \, d\Omega \right| \\
&\leq C_3 \left[ \int_{\Omega} \left( \int_{a}^{x} g(\xi, t) \, d\xi \right)^2 \, d\Omega \right]^{1/2} \\
&\quad \times \left[ \int_{\Omega} \left\{ u_x^2 + \frac{1}{k} \left( \int_{a}^{x} c u_t \, d\xi \right)^2 \right\} \, c \Omega \right]^{1/2} \\
&\leq C_4 \left| f \left| \wt{S}^{-1,0}_{a,-} W_2(\Omega, \Gamma_l) \right| \right| \left| u \right| \overset{\circ}{\rightarrow} W_2^{\wt{A}}(\Omega; \Gamma_r, T) \right|.
\end{align}

\begin{align}
&= \left| \int_{0}^{T} \psi(t) \left\{ u(a, t) - \int_{\gamma(t)}^{a} \frac{d\theta}{k(\theta, t)} \int_{a}^{\theta} c(\xi) u_t(\xi, t) \, d\xi \right\} \, dt \right| \\
&\leq C_6 \left| f \int_{\Omega} \left| \wt{S}^{-1,0}_{a,-} W_2(\Omega, \Gamma_l) \right| \right| \left| u \right| \overset{\circ}{\rightarrow} W_2^{\wt{A}}(\Omega; \Gamma_r, T) \right|.
\end{align}
Unnumbered align, with a number on the second \texttt{split}:

\begin{align*}
|I_1| &= \left| \int_{\Omega} g Ru \, d\Omega \right|
\leq C_3 \left[ \int_{\Omega} \left( \int_{a}^{x} g(\xi,t) \, d\xi \right)^2 \, d\Omega \right]^{1/2}
\times \left[ \int_{\Omega} \left\{ u_x^2 + \frac{1}{k} \left( \int_{a}^{x} cu_t \, d\xi \right)^2 \right\} c \, d\Omega \right]^{1/2}
\leq C_4 \left\| \int \left\{ \tilde{S}_{a,-}^{-1,0} W_2(\Omega, \Gamma_l) \right\} \left\| u \right\| \overset{\circ}{\rightarrow} W_2^A(\Omega; \Gamma_r, T) \right\|.
|I_2| &= \left| \int_{0}^{T} \psi(t) \left\{ u(a,t) - \int_{\gamma(t)}^{a} \frac{d\theta}{k(\theta,t)} \int_{a}^{\theta} c(\xi) u_t(\xi,t) \, d\xi \right\} dt \right|
\leq C_6 \left\| \int_{\Omega} \left\{ \tilde{S}_{a,-}^{-1,0} W_2(\Omega, \Gamma_l) \right\} \left\| u \right\| \overset{\circ}{\rightarrow} W_2^A(\Omega; \Gamma_r, T) \right\|.
\end{align*}

Some text after to test the below-display spacing.

\begin{align*}
|I_1| &= \left| \int_{\Omega} g Ru \, d\Omega \right|
\leq C_3 \left[ \int_{\Omega} \left( \int_{a}^{x} g(\xi,t) \, d\xi \right)^2 \, d\Omega \right]^{1/2}
\times \left[ \int_{\Omega} \left\{ u_x^2 + \frac{1}{k} \left( \int_{a}^{x} cu_t \, d\xi \right)^2 \right\} c \, d\Omega \right]^{1/2}
\leq C_4 \left\| \int \left\{ \tilde{S}_{a,-}^{-1,0} W_2(\Omega, \Gamma_l) \right\} \left\| u \right\| \overset{\circ}{\rightarrow} W_2^A(\Omega; \Gamma_r, T) \right\|.
|I_2| &= \left| \int_{0}^{T} \psi(t) \left\{ u(a,t) - \int_{\gamma(t)}^{a} \frac{d\theta}{k(\theta,t)} \int_{a}^{\theta} c(\xi) u_t(\xi,t) \, d\xi \right\} dt \right|
\leq C_6 \left\| \int_{\Omega} \left\{ \tilde{S}_{a,-}^{-1,0} W_2(\Omega, \Gamma_l) \right\} \left\| u \right\| \overset{\circ}{\rightarrow} W_2^A(\Omega; \Gamma_r, T) \right\|.
\end{align*}

(67')
A.2 Multline

Numbered version:
\[
\int_a^b \left\{ \int_a^b \left[ f(x)^2 g(y)^2 + f(y)^2 g(x)^2 \right] - 2f(x)g(x)f(y)g(y) \, dx \right\} \, dy \\
= \int_a^b \left\{ g(y)^2 \int_a^b f^2 + f(y)^2 \int_a^b g^2 - 2f(y)g(y) \int_a^b fg \right\} \, dy \tag{68}
\]

To test the use of \texttt{\label} and \texttt{\ref}, we refer to the number of this equation here: (68).

\begin{multline}
\label{eq:E}
\int_a^b \left\{ \int_a^b \left[ f(x)^2 g(y)^2 + f(y)^2 g(x)^2 \right] - 2f(x)g(x)f(y)g(y) \, dx \right\} \, dy \\
= \int_a^b \left\{ g(y)^2 \int_a^b f^2 + f(y)^2 \int_a^b g^2 - 2f(y)g(y) \int_a^b fg \right\} \, dy
\end{multline}

Unnumbered version:
\[
\int_a^b \left\{ \int_a^b \left[ f(x)^2 g(y)^2 + f(y)^2 g(x)^2 \right] - 2f(x)g(x)f(y)g(y) \, dx \right\} \, dy \\
= \int_a^b \left\{ g(y)^2 \int_a^b f^2 + f(y)^2 \int_a^b g^2 - 2f(y)g(y) \int_a^b fg \right\} \, dy
\]

Some text after to test the below-display spacing.

\begin{multline*}
\int_a^b \left\{ \int_a^b \left[ f(x)^2 g(y)^2 + f(y)^2 g(x)^2 \right] - 2f(x)g(x)f(y)g(y) \, dx \right\} \, dy \\
= \int_a^b \left\{ g(y)^2 \int_a^b f^2 + f(y)^2 \int_a^b g^2 - 2f(y)g(y) \int_a^b fg \right\} \, dy
\end{multline*}
A.3 Gather

Numbered version with \texttt{\notag} on the second line:

\begin{align}
D(a,r) & \equiv \{ z \in \mathbb{C} : |z - a| < r \}, \\
seg(a,r) & \equiv \{ z \in \mathbb{C} : 3z = 3a, |z - a| < r \}, \\
c(e,\theta,r) & \equiv \{(x,y) \in \mathbb{C} : |x - e| < y \tan \theta, 0 < y < r \}, \\
C(E,\theta,r) & \equiv \bigcup_{e \in E} c(e,\theta,r).
\end{align}

Unnumbered version.

\begin{align*}
D(a,r) & \equiv \{ z \in \mathbb{C} : |z - a| < r \}, \\
seg(a,r) & \equiv \{ z \in \mathbb{C} : 3z = 3a, |z - a| < r \}, \\
c(e,\theta,r) & \equiv \{(x,y) \in \mathbb{C} : |x - e| < y \tan \theta, 0 < y < r \}, \\
C(E,\theta,r) & \equiv \bigcup_{e \in E} c(e,\theta,r).
\end{align*}
A.4 Align

Numbered version:

\[\gamma_x(t) = (\cos tu + \sin tx, v),\quad (72)\]
\[\gamma_y(t) = (u, \cos tv + \sin ty),\quad (73)\]
\[\gamma_z(t) = \left( \cos tu + \frac{\alpha}{\beta} \sin tv, -\frac{\beta}{\alpha} \sin tu + \cos tv \right).\quad (74)\]

Some text after to test the below-display spacing.

\begin{align}
\gamma_x(t) &= (\cos tu + \sin tx, v), \\
\gamma_y(t) &= (u, \cos tv + \sin ty), \\
\gamma_z(t) &= \left( \cos tu + \frac{\alpha}{\beta} \sin tv, -\frac{\beta}{\alpha} \sin tu + \cos tv \right).
\end{align}

Unnumbered version:

\[
\gamma_x(t) = (\cos tu + \sin tx, v),
\]
\[
\gamma_y(t) = (u, \cos tv + \sin ty),
\]
\[
\gamma_z(t) = \left( \cos tu + \frac{\alpha}{\beta} \sin tv, -\frac{\beta}{\alpha} \sin tu + \cos tv \right).
\]

Some text after to test the below-display spacing.

\begin{align*}
\gamma_x(t) &= (\cos tu + \sin tx, v), \\
\gamma_y(t) &= (u, \cos tv + \sin ty), \\
\gamma_z(t) &= \left( \cos tu + \frac{\alpha}{\beta} \sin tv, -\frac{\beta}{\alpha} \sin tu + \cos tv \right).
\end{align*}

A variation:

\[x = y \quad \text{by (84)} \quad (75)\]
\[x' = y' \quad \text{by (85)} \quad (76)\]
\[x + x' = y + y' \quad \text{by Axiom 1.} \quad (77)\]

Some text after to test the below-display spacing.

\begin{align}
x & = y \quad \text{by \ref{eq:C}} \\
x' & = y' \quad \text{by \ref{eq:D}} \\
x + x' & = y + y' \quad \text{by Axiom 1.}
\end{align}
A.5 Align and split within gather

When using the \texttt{align} environment within the \texttt{gather} environment, one or the other, or both, should be unnumbered (using the $\ast$ form); numbering both the outer and inner environment would cause a conflict.

Automatically numbered \texttt{gather} with \texttt{split} and \texttt{align}$\ast$:

$$\varphi(x,z) = z - \gamma_{10}x - \gamma_{mn}x^mz^n = z - Mr^{-1}x - Mr^{-(m+n)}x^mz^n$$

$$\zeta^0 = (\xi^0)^2, \quad \zeta^1 = \xi^0\xi^1, \quad \zeta^2 = (\xi^1)^2,$$

(78)

Here the \texttt{split} environment gets a number from the outer \texttt{gather} environment; numbers for individual lines of the \texttt{align}$\ast$ are suppressed because of the star.

\begin{verbatim}
\begin{gather}
\begin{split}
\varphi(x,z) &= z - \gamma_{10}x - \gamma_{mn}x^mz^n \\
&= z - Mr^{-1}x - Mr^{-(m+n)}x^mz^n \\
\end{split} \\
\end{gather}
\begin{align*}
\zeta^0 &= (\xi^0)^2, \\
\zeta^1 &= \xi^0\xi^1, \\
\zeta^2 &= (\xi^1)^2,
\end{align*}
\end{verbatim}

The $\ast$-ed form of \texttt{gather} with the non-$\ast$-ed form of \texttt{align}.

$$\varphi(x,z) = z - \gamma_{10}x - \gamma_{mn}x^mz^n = z - Mr^{-1}x - Mr^{-(m+n)}x^mz^n$$

$$\zeta^0 = (\xi^0)^2, \quad \zeta^1 = \xi^0\xi^1, \quad \zeta^2 = (\xi^1)^2,$$

(79) (80) (81)

Some text after to test the below-display spacing.

\begin{verbatim}
\begin{gather*}
\begin{split}
\varphi(x,z) &= z - \gamma_{10}x - \gamma_{mn}x^mz^n \\
&= z - Mr^{-1}x - Mr^{-(m+n)}x^mz^n \\
\end{split} \\
\end{gather*}
\end{verbatim}
\begin{align*}
\zeta^1 &= \xi^0 \xi^1, \\
\zeta^2 &= (\xi^1)^2,
\end{align*}
A.6 Alignat

Numbered version:

\begin{alignat}{3}
  V_i &= v_i - q_i v_j, & X_i &= x_i - q_i x_j, & U_i &= u_i, \quad \text{for } i \neq j; \label{eq:B} \\
  V_j &= v_j, & X_j &= x_j, & U_j &= u_j + \sum_{i \neq j} q_i u_i. \\
\end{alignat}

Unnumbered version:

\begin{alignat*}{3}
  V_i &= v_i - q_i v_j, & X_i &= x_i - q_i x_j, & U_i &= u_i, \quad \text{for } i \neq j; \\
  V_j &= v_j, & X_j &= x_j, & U_j &= u_j + \sum_{i \neq j} q_i u_i. \\
\end{alignat*}
The most common use for \texttt{alignat} is for things like

\begin{alignat}{2}
  x &= y & \quad \text{by (66)} & \quad \text{(84)} \\
  x' &= y' & \quad \text{by (82)} & \quad \text{(85)} \\
  x + x' &= y + y' & \quad \text{by Axiom 1.} & \quad \text{(86)}
\end{alignat}

Some text after to test the below-display spacing.

\begin{alignat}{2}
  x &= y & \quad \text{(by (66))} \\
  x' &= y' & \quad \text{(by (82))} \\
  x + x' &= y + y' & \quad \text{(by Axiom 1.)}
\end{alignat}
References


