

PATHWISE STOCHASTIC CALCULUS WITH LOCAL TIMES

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ABSTRACT. We study a notion of local time for a continuous path, defined as a limit of suitable discrete quantities along a general sequence of partitions of the time interval. Our approach subsumes other existing definitions and agrees with the usual (stochastic) local times a.s. for paths of a continuous semimartingale. We establish pathwise version of the Itô-Tanaka, change of variables and change of time formulae. We provide equivalent conditions for existence of pathwise local time. Finally, we study in detail how the limiting objects, the quadratic variation and the local time, depend on the choice of partitions. In particular, we show that an arbitrary given non-decreasing process can be achieved a.s. by the pathwise quadratic variation of a standard Brownian motion for a suitable sequence of (random) partitions; however, such degenerate behavior is excluded when the partitions are constructed from stopping times.

1. INTRODUCTION

In a seminal paper, Föllmer [11] pioneered a non-probabilistic approach to stochastic calculus. For a function of real variable x , he introduced a notion of quadratic variation $\langle x \rangle_t$ along a sequence of partitions $(\pi_n)_n$ and proved the associated Itô's formula for $f \in C^2$:

$$(1.1) \quad f(x_t) - f(x_0) = \int_0^t f'(x_s) dx_s + \frac{1}{2} \int_0^t f''(x_s) d\langle x \rangle_s,$$

where the integral $\int_0^t f'(x_s) dx_s$ is defined as the limits of non-anticipative Riemann sums, shown to exist whenever $\langle x \rangle_t$ exists. Föllmer also observed that a path of a semimartingale a.s. admits quadratic variation in the pathwise sense and the usual stochastic integral agrees with his pathwise integral a.s.

The underlying motivation behind our current study was to extend the pathwise stochastic integral and its Itô's formula to functions f which are not in C^2 . This question arose from applications in mathematical finance (see Davis et al. [8]) but, we believe, is worth pursuing for its own sake. It led us to develop pathwise stochastic calculus featuring local times, which is the first main contribution of our work. We define a notion of local time $L_t^x(u)$ for a function x , prove the associated Itô-Tanaka formula and show that a path of a continuous semimartingale X a.s. admits pathwise local time $L_t^{X(\omega)}(u)$ which then agrees with the usual (stochastic) local time. Our contribution should be seen in the context of three previous connected works. First, our results are related to Bertoin [3], although the analysis there had a different spirit. Second, similar results appeared in the unpublished diploma thesis of Wuermli [28]. The approach is the same, however the proof in [28] was complicated and applied only to square integrable martingales. We also have a slightly different

Date: First version: 16 May 2012. This version: August 26, 2015.

This research has been generously supported by the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement no. 335421. Jan Oblój is also grateful to the Oxford-Man Institute of Quantitative Finance and St John's College in Oxford for their financial support. The authors thank Hans Föllmer and Vladimir Vovk for helpful comments and advice at various stages of this work.

definition of local time which includes continuity in time and importantly we consider convergence in L^p for $p \in [1, \infty)$ instead of just $p = 2$. This allows us to capture the tradeoff between the generality of paths considered and the scope of applicability of the Itô-Tanaka formula. Further, we investigate many questions not considered in [28], as explained below. Third, and more recently, related results appeared in Perkowski and Prömel [20]. However in [20], the authors proposed a different definition of pathwise local time and in consequence the conclusion of their main theorem (Theorem 3.5 in [20]) on the existence of $L_t^{X(\omega)}(u)$ for a.e. ω is stronger than ours. In contrast, our Theorem 6.1 applies to a general semimartingale X , whereas results in [20] apply only if X is a local martingale either under the original probability $\mathbb{P}$ or under some $\mathbb{Q} \gg \mathbb{P}$ (see [20, Remark 3.6]).

The main advantage of our definition, as compared with these previous works, is that we are able to characterise the existence of pathwise local time with a number of equivalent conditions (see Theorem 3.1). This feature seems to be entirely new. It allowed us in particular to build an explicit example of a path which admits quadratic variation but not the local time. Also, while [8] and [28] (following [11]) consider partitions π_n whose mesh is going to zero (which are well suited for changing variables), the results [3, Theorem 3.1] and [20, Theorem 3.5] of existence of pathwise local time consider Lebesgue¹ partitions. Since neither type of partition is a special case of the other, this makes the results in these papers hard to compare. We solve this conundrum by proving our existence result (Theorem 6.1) for a general type of partition, which subsumes both types considered above. Finally, we prove that the existence of $L_t(u)$ is preserved by a C^1 change of variables (improving on [8, Proposition B.6]) and by time changes, and that $g \rightarrow \int_0^t g(x_s)dx_s$ is continuous (similarly² to [20]).

The second main pursuit of this paper is Theorem 7.1, which is connected with the theory above but we believe to be of independent interest. This states that if W is Brownian motion, A is *any* increasing $[0, \infty]$ -valued measurable process with $A_0 = 0$ and

$$\langle W \rangle_t^\pi := \sum_{t_j \in \pi} (W_{t_{j+1} \wedge t} - W_{t_j \wedge t})^2,$$

then there exist refining partitions $(\pi_n)_n$ made of *random* times s.t. $\langle W \rangle_t^{\pi_n} \rightarrow A_t$ a.s. for all t . This result is meant to illustrate, in the most stark way possible, the dependence of the pathwise quadratic variation (and thus of the pathwise local time) on the partitions $(\pi_n)_n$. This may push the reader to dismiss the notion of pathwise quadratic variation (and local time); we feel then that it worthwhile pointing out that, if we restrict ourselves to partitions constructed from *stopping* times, the limit of $\langle W \rangle_t^{\pi_n}$ exists and is independent of the choice of partitions, as it always equals t . Analogously, our Theorem 6.1 states that, if we only consider partitions constructed from stopping times, the pathwise local time $L_t^{X(\omega)}(u)$ of a semimartingale X exists and is independent of the choice of partitions, as it coincides with the classical local time.

As already known by Lévy, $\inf_\pi \langle x \rangle_1^\pi = 0$ for every continuous function x and $\sup_\pi \langle W(\omega) \rangle_1^\pi = \infty$ for a.e. ω . Our Theorem 7.1 builds on these facts and answers in particular two questions which they leave open: whether for the general path $x = W(\omega)$ one can make $\langle x \rangle_1^{\pi_n}$ converge to any chosen $C = C(\omega) \in \mathbb{R}$, and what dependence in t we can expect for $\lim_n \langle x \rangle_t^{\pi_n}$. Specifically it is clear that it must be an increasing functions, and we wondered whether it is automatically continuous;

¹Which we define in (2.2).

²Note that due to difference in definitions of local time, we use different topologies.

indeed, while we followed Föllmer [11], who carefully *required* that $\lim_n \langle x \rangle_t^{\pi_n}$ be continuous³, several authors who cite [11] do not (see for example [3], [8], [24]); our Theorem 7.1 shows that this is a significant omission.

The plan for rest of the paper is as follows. In Section 2 we introduce most of the notations and definitions, and recall parts of [11]. In Section 3 we identify several conditions equivalent to the existence of pathwise local time, prove the Itô-Tanaka formula and the continuity of $g \rightarrow \int_0^t g(x_s) dx_s$. In Section 4 we consider change of variable and time, and in Section 5 we extend Itô-Tanaka formula from the case of a Sobolev function f to the case where f is a difference of convex functions. In Section 6 we prove that a path of a semimartingale a.s. admits the pathwise local time, and relate this to the downcrossing representation of semimartingale local time proved by Lévy. Finally in Section 7 we state precisely our Theorem 7.1 about $\langle W \rangle_t^{\pi_n} \rightarrow A_t$, and we explain the idea behind its proof avoiding all the complications which arise from tracking the dependence in ω (measurability and null sets); in the appendix we provide its actual proof.

2. PATHWISE STOCHASTIC CALCULUS

In this section we introduce most notations and definitions used throughout the article, and we revisit the part of [11] which deals with continuous functions, slightly refining its results to include uniformity in t and more general partitions.

By measure we mean sigma-additive positive measure; a Radon measure will be the difference of two measures which are finite on compact sets. With $|\mu|$ we will denote the total-variation measure relative to a ‘real measure’ μ (i.e. μ is the difference of two measures), and with $\max(\mu, 0)$ the measure $(\mu + |\mu|)/2$ (i.e. the positive part in the Hahn-Jordan decomposition of μ). We will say that $g_n \rightarrow g$ *fast* in $L^p(\mu)$ if $\sum_{n \in \mathbb{N}} \|g_n - g\|_{L^p(\mu)}^p < \infty$; this trivially implies that $g_n \rightarrow g$ a.s. and in $L^p(\mu)$. We will denote by $\mathcal{B}$ (resp. $\mathcal{B}_T$) the Borel sets of $[0, \infty)$ (resp. $[0, T]$). For a continuous function $x = (x_t)_{t \geq 0}$, m_T and M_T are respectively the minimum and maximum over $t \in [0, T]$. We set $x_\infty = 0$, denote by δ_t the Dirac measure at t , and by π a partition of $[0, \infty)$, i.e. $\pi = (t_k)_{k \in \mathbb{N}}$ where $t_k \in [0, \infty]$, $t_0 = 0$, $t_k < t_{k+1}$ if $t_{k+1} < \infty$, and $\lim_{k \rightarrow \infty} t_k = \infty$. For such x and π , we set

$$(2.1) \quad O_t(x, \pi) := \max\{|x(b) - x(a)| : a, b \in [t_j, t_{j+1}) \cap [0, t]\}.$$

Föllmer works with a sequence of finite partitions $(\pi_n)_n$ whose step on compacts converges to zero. This excludes the most commonly used partitions: the *Lebesgue partitions*, i.e., those of the form $\pi_P = \pi_P(x) = (\tau_k)_{k \in \mathbb{N}}$,

$$(2.2) \quad \text{where } \tau_0 := 0, \tau_{k+1} := \inf\{t > \tau_k : x_t \in P, x_t \neq x_{\tau_k}\}$$

for some P partition of $\mathbb{R}$, i.e., $P = (p_k)_{k \in \mathbb{Z}}$ with

$$p_k \in [-\infty, \infty], \lim_{k \rightarrow \pm\infty} p_k = \pm\infty, p_0 = 0, \text{ and } p_k < p_{k+1} \text{ if } p_k, p_{k+1} \in \mathbb{R}.$$

We will work instead with partitions π_n such that $O_T(x, \pi_n) \rightarrow 0$ for all $T < \infty$; these are very flexible, as they subsume both Lebesgue partitions and the ones used by Föllmer. Moreover they allow us to obtain time-change results, and have the additional advantage that one can always pass to refinements (since if $\pi \subseteq \pi'$ then $O_T(x, \pi) \geq O_T(x, \pi')$).

While our aim in this paper is to develop a pathwise, non-probabilistic, theory, it is often the case that we want to consider paths that arise as sample functions of some

³More precisely [11] deals with càdlàg x and requires that μ_n converge weakly to a measure μ which assigns mass $(\Delta x_t)^2$ to the singleton $\{t\}$; if x is continuous this implies continuity of $\langle x \rangle_t^\pi$.

stochastic process. Such processes are assumed to be defined on some underlying filtered probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t \in [0, \infty)}, \mathbb{P})$ satisfying the ‘usual conditions’. We denote by $\int_0^t H_s dX_s$ the stochastic integral of a predictable and locally-bounded integrand H with respect to a continuous semimartingale $X = (X_t)_{t \geq 0}$. Inequalities between random variables are tacitly supposed to hold for $\mathbb{P}$ -almost every ω . A sequence of partitions of $[0, \infty)$ made of random (resp. stopping) times will be called a *random* (resp. *optional*) *partition* of $[0, \infty)$; more precisely if $\pi = (\tau_k)_{k \in \mathbb{N}}$, where τ_k are $[0, \infty]$ -valued random variables such that $\tau_0 = 0, \tau_k \leq \tau_{k+1}$ with $\tau_k < \tau_{k+1}$ on $\{\tau_{k+1} < \infty\}$, and $\lim_{k \rightarrow \infty} \tau_k = \infty$, then π is called a random partition, and if moreover $\{\tau_k \leq t\} \in \mathcal{F}_t$ for all k, t then π is an optional⁴ partition.

Definition 2.1. *Given a continuous function $x : [0, \infty) \rightarrow \mathbb{R}$ and a sequence of partitions $\Pi = (\pi_n)_n$ such that $O_T(x, \pi_n)$ converges to zero as $n \rightarrow \infty$ for all $T < \infty$, we will say that x has quadratic variation (sampled along Π) if the measures*

$$(2.3) \quad \mu_n := \sum_{t_j \in \pi_n} (x_{t_{j+1}} - x_{t_j})^2 \delta_{t_j}$$

converge vaguely⁵ to a measure without atoms μ as $n \rightarrow \infty$. We will write $x \in \mathcal{Q}$ if $O_T(x, \pi_n) \rightarrow 0$ for all $T < \infty$ and x has quadratic variation.

Recall that μ_n converges weakly to a non-atomic measure μ iff its cumulative distribution function converges pointwise to a continuous function, and thus iff

$$\langle x \rangle_t^{\pi_n} := \sum_{t_j \in \pi_n} (x_{t_{j+1} \wedge t} - x_{t_j \wedge t})^2$$

converges pointwise to a *continuous* (increasing) function $\langle x \rangle_t$; the cumulative distribution function of μ is then $\langle x \rangle$, and is called the quadratic variation of x . Such convergence is then always uniform in t , and more generally for every $T > 0$ and continuous function $f : [m_T, M_T] \rightarrow \mathbb{R}$

$$(2.4) \quad \sum_{t_j \in \pi_n} f(x_{t_j}) (x_{t_{j+1} \wedge t} - x_{t_j \wedge t})^2 \longrightarrow \int_0^t f(x_s) d\langle x \rangle_s \text{ uniformly in } t \in [0, T] :$$

indeed if $t_j \leq t < t_{j+1}$ the sum on the left of (2.4) differs from $\int_0^t f d\mu_n$ of at most

$$|f(x_{t_j})((x_{t_{j+1}} - x_{t_j})^2 - (x_t - x_{t_j})^2)| \leq 2\|f\|_\infty O_T(x, \pi_n)^2,$$

and $\int_0^t f d\mu_n$ converges to $\int_0^t f d\mu$ uniformly in $t \leq T$ as the following simple observation applied to the positive and negative parts of f shows.

Scholium 2.2. *[Polya] Let $F, F_n : [0, T] \rightarrow \mathbb{R}$ be càdlàg increasing. If F is continuous and $F_n \rightarrow F$ pointwise then the convergence is uniform in $t \in [0, T]$.*

Note that a priori $\mu, \langle x \rangle$ and $\mathcal{Q}$ depend on $\Pi = (\pi_n)_n$; when we want to stress this dependence, we will write $\mu^\Pi, \langle x \rangle^\Pi, \mathcal{Q}^\Pi$. Note also that the series in (2.4) is in fact a finite sum, since every partition is finite on compacts.

We introduce now some more notation which will be used throughout and will be particularly useful in the proof of Theorem 7.1 in Appendix A. Given numbers $a \leq s \leq t \leq b$ and a finite partition π of $[a, b]$ (meaning $\pi = (t_i)_{i=0}^k$ with $t_0 = a, t_i < t_{i+1}$ for all i , and $t_k = b$) we set

$$(2.5) \quad \langle x \rangle_{[s, t]}^\pi := \sum_i (x_{(t_{i+1} \wedge t) \vee s} - x_{(t_i \wedge t) \vee s})^2;$$

⁴The rationale behind this uncommon terminology is that that τ is a stopping time iff $\mathbf{1}_{\{\tau \leq \cdot\}}$ is an optional process.

⁵Meaning that $\int f d\mu_n \rightarrow \int f d\mu$ for every continuous function f with compact support.

if $s = a$ and $t = b$ the latter expression simplifies and we denote it with

$$\langle x \rangle_\pi := \langle x \rangle_{(a,b]}^\pi = \sum_i (x_{t_{k+1}} - x_{t_k})^2.$$

Notice that if π is a partition of $[a, b] \ni s, t$ then

$$(2.6) \quad \langle x \rangle_{(a,b]}^\pi = \langle x \rangle_{(a,s]}^\pi + \langle x \rangle_{(s,b]}^\pi \quad \text{if } s \in \pi;$$

in particular

$$(2.7) \quad \langle x \rangle_{(s,t]}^\pi \leq \langle x \rangle_{(a,b]}^\pi \quad \text{if } s, t \in \pi,$$

and if $\tilde{\pi}$ is a partition of $[b, c]$ then

$$(2.8) \quad \langle x \rangle_{(a,c]}^{\pi \cup \tilde{\pi}} = \langle x \rangle_{(a,b]}^\pi + \langle x \rangle_{(b,c]}^{\tilde{\pi}}.$$

We shall now see that the quadratic variation sampled along optional partitions $(\pi_n)_n$ exists on a.e. path of a semimartingale, and that a.e. it does not depend on $(\pi_n)_n$; this is essentially the usual result on the existence of the quadratic variation for a semimartingale.

Proposition 2.3. *Let X be a continuous semimartingale and $\langle X \rangle_t := X_t^2 - 2 \int_0^t X_s dX_s$. If $\Pi = (\pi_n)_n$ are optional partitions such that $O_T(X, \pi_n) \rightarrow 0$ a.s. for all $T < \infty$ then there exists some subsequence $(n_k)_k$ such that, for each ω outside a $\mathbb{P}$ -null set and setting $\Pi' := (\pi_{n_k})_k$, we have $X(\omega) \in \mathcal{Q}^{\Pi'}$ and $\langle X(\omega) \rangle^{\Pi'} = \langle X \rangle(\omega)$.*

Proof. Write $\pi_n = (\tau_j^n)_j$, take $H^n := \sum_j X_{\tau_j^n} \mathbf{1}_{(\tau_j^n, \tau_{j+1}^n]}$ and notice that

$$(2.9) \quad 2 \int_0^t X dX + \langle X \rangle_t = X_t^2 = 2 \int_0^t H^n dX_t + \langle X \rangle_t^{\pi_n}.$$

Since H^n converges pointwise to X and is bounded by a locally bounded predictable process⁶, the stochastic dominated convergence theorem gives that $\int_0^\cdot H^n dX$ converges to $\int_0^\cdot X dX$ uniformly on compacts in probability, which implies the thesis. $\square$

We now show that one can identify some of the subsubsequences along which the previous statement holds; in particular this holds when π_n is the Lebesgue partition π_{D_n} corresponding to $D_n := 2^{-n}\mathbb{N}$ (the dyadics of order n). Given $p \in [1, \infty)$ we denote by $\mathcal{S}^p$ the set of continuous semimartingales $X = (X_t)_{t \in [0, T]}$ which satisfy

$$\|X\|_{\mathcal{S}^p} := \left\| [M]_T^{1/2} \right\|_{L^p} + \left\| \int_0^T d|V|_t \right\|_{L^p} < \infty,$$

where $|V|_T$ is the variation of $(V_t)_{t \in [0, T]}$ and $X = M + V$ is the canonical semimartingale decomposition of X . We recall the inequality

$$(2.10) \quad \left\| \sup_{t \leq T} |X_t| \right\|_{L^p(\mathbb{P})} \leq C_p \|X\|_{\mathcal{S}^p},$$

which holds for local martingales (this being one side of the celebrated Burkholder-Davis-Gundy inequalities) and thus trivially extends to $X \in \mathcal{S}^p$. We will also use without further mention that if H is locally-bounded and predictable then the canonical decomposition of $\int_0^\cdot H dX$ is $\int_0^\cdot H dM + \int_0^\cdot H dV$ and so

$$\left\| \int_0^\cdot H dX \right\|_{\mathcal{S}^p} = \left\| \left(\int_0^\cdot H_t^2 d[M]_t \right)^{1/2} \right\|_{L^p} + \left\| \int_0^\cdot |H_t| d|V|_t \right\|_{L^p}.$$

Proposition 2.4. *If in Proposition 2.3 we make the stronger assumption that $\sum_n O_T(X, \pi_n) < \infty$ a.s. for all $T < \infty$ then $X(\omega) \in \mathcal{Q}^\Pi$ and $\langle X(\omega) \rangle^\Pi = \langle X \rangle(\omega)$ for a.e. ω .*

⁶For example $|H_t^n| \leq X_t^*$ with $X_t^* := \sup_{s \leq t} |X_s|$.

Proof. Fix a compact time interval $[0, T]$ on which we will work. By prelocalizing we can assume that $X \in \mathcal{S}^4$ (see⁷ Emery [9, Theoreme 2]) and passing to an equivalent probability we can moreover⁸ assume that $K := \sum_n O_T(X, \pi_n) \in L^4$. Take H^n as in Proposition 2.3, $K^n := H^n - X$ and notice that $\sup_t |K_t^n| \leq O_T(X, \pi_n)$, so $\sum_n \sup_t |K_t^n| \leq K$ and in particular $\sum_n \sup_t |K_t^n|^2 \leq K^2 \in L^2$. Using (2.10) and $(a+b)^2 \leq 2(a^2 + b^2)$ gives that $\sup_t |\int_0^t K^n dX|$ converges to zero fast in L^2 if

$$\sum_n \mathbb{E}(\int (K^n)^2 d[M] + (\int K^n d|V|)^2)$$

is finite, which is true since it is bounded above by $\mathbb{E}(K^2([M]_T + |V|_T^2))$, which is finite by Hölder inequality since $K \in L^4, X \in \mathcal{S}^4$. Since $\sup_{t \leq T} |\int_0^t K^n dX| \rightarrow 0$ fast in L^2 and thus a.s., (2.9) yields $\sup_{t \leq T} |\langle X \rangle_t^{\pi_n} - \langle X \rangle_t| \rightarrow 0$ a.s.. $\square$

Theorem 2.5 (Föllmer [11]). *If $x \in \mathcal{Q}$, $g \in C^1$ and $t \in [0, \infty)$ the limit*

$$(2.11) \quad \lim_n \sum_{t_j \in \pi_n} g(x_{t_j})(x_{t_{j+1} \wedge t} - x_{t_j \wedge t})$$

exists uniformly on compacts and defines a continuous function of t denoted $\int_0^t g(x_s) dx_s$. This integral satisfies Itô's formula: for $f \in C^2(\mathbb{R})$,

$$(2.12) \quad f(x_t) - f(x_0) = \int_0^t f'(x_s) dx_s + \frac{1}{2} \int_0^t f''(x_s) d\langle x \rangle_s.$$

Notice that the series defining the Föllmer integral in (2.11) and later in this paper are in fact finite sums, since every partition is finite on compacts.

Proof. By using the second order Taylor's expansion write

$$(2.13) \quad \sum_{t_j \in \pi_n} f(x_{t_{j+1} \wedge t}) - f(x_{t_j \wedge t})$$

as

$$(2.14) \quad \sum_{t_j \in \pi_n} f'(x_{t_j})(x_{t_{j+1} \wedge t} - x_{t_j \wedge t}) + \frac{1}{2} \sum_{t_j \in \pi_n} f''(x_{t_j})(x_{t_{j+1} \wedge t} - x_{t_j \wedge t})^2 + C_n(t),$$

where the correction term $C_n(t)$ is bounded by

$$(2.15) \quad \sum_{t_j \in \pi_n} \phi(|x_{t_{j+1} \wedge t} - x_{t_j \wedge t}|)(x_{t_{j+1} \wedge t} - x_{t_j \wedge t})^2$$

for some increasing function ϕ which is continuous at 0 and such that $\phi(0) = 0$. Since $x \in \mathcal{Q}^{(\pi_n)_n}$, the term (2.15) converges to 0 (for $t = T$, and thus also uniformly in $t \leq T$). Since (2.4) states that the second term of (2.14) converges to the last term of (2.12) uniformly on compacts, by difference the first term of (2.14) also converges, uniformly on compacts; moreover (2.12) holds since the telescopic sum (2.13) equals $f(x_t) - f(x_0)$. $\square$

Remark that Föllmer [11] considers sums of the form

$$\sum_{\pi_n \ni t_j \leq t} g(x_{t_j})(x_{t_{j+1}} - x_{t_j}) \quad \text{and} \quad \sum_{\pi_n \ni t_j \leq t} g(x_{t_j})(x_{t_{j+1}} - x_{t_j})^2,$$

whereas we consider

$$(2.16) \quad \sum_{t_j \in \pi_n} g(x_{t_j})(x_{t_{j+1} \wedge t} - x_{t_j \wedge t}) \quad \text{and} \quad \sum_{t_j \in \pi_n} g(x_{t_j})(x_{t_{j+1} \wedge t} - x_{t_j \wedge t})^2.$$

⁷This statement also appears in [21, Chapter 5, Theorem 14], without proof.

⁸If $X \in \mathcal{S}^4(\mathbb{P})$ and $(d\mathbb{Q}/d\mathbb{P})(\omega) := C \exp(-K(\omega))$ then $K \in L^4(\mathbb{Q})$, and $X \in \mathcal{S}^4(\mathbb{Q})$ since $d\mathbb{Q}/d\mathbb{P} \in L^\infty(\mathbb{P})$.

Since the difference between these two sums is

$$g(x_{t_i})(x_{t_{i+1}} - x_t) \text{ and } g(x_{t_i})((x_{t_{i+1}} - x_{t_i})^2 - (x_{t_{i+1}} - x_t)^2)$$

(where $i := \max\{j : \pi_n \ni t_j \leq t\}$), which goes to zero as $O_T(x, \pi_n) \rightarrow 0$, these expressions are equal in the limit. The reason we prefer to stick with (2.16) is that it involves only non-anticipative quantities (i.e. their value of time t does not depend on the value of x at later times), which better fits in the theory of stochastic integration and thus allow us to obtain formulae like (2.9) and (6.8).

3. PATHWISE LOCAL TIME

As already suggested in [11], there should be an extension of ‘Itô formula’ valid also when f'' is not a continuous functions, as it is in (2.12). In the theory of continuous semimartingales, such an extension proceeds via local time and the Tanaka-Meyer formula; what follows is a pathwise version.

If f'_- is the left-derivative of a convex function f , and f'' is the second derivative of f in the sense of distributions (i.e. the unique positive Radon measure which satisfies $f''([a, b]) = f'_-(b) - f'_-(a)$) we obtain for $a \leq b$

$$\begin{aligned} f(b) - f(a) &= \int_a^b f'_-(y) dy = \int_a^b \left(f'_-(a) + \int_{[a, y)} f''(du) \right) dy \\ &= f'_-(a)(b - a) + \int_{[a, b)} (b - u) f''(du) \quad , \text{ so that} \\ f(b) - f(a) &= f'_-(a)(b - a) + \int_{-\infty}^{\infty} \mathbf{1}_{[a \wedge b, a \vee b)}(u) |b - u| f''(du), \quad \forall a, b \in \mathbb{R}. \end{aligned}$$

So if given a function x and a partition $\pi = (t_j)_j$, we set for $u, v \in \mathbb{R}$

$$\llbracket u, v \rrbracket := \begin{cases} [u, v), & \text{if } u \leq v, \\ [v, u), & \text{if } u > v, \end{cases}$$

and define the discrete local time (along π) as

$$(3.1) \quad L_t^\pi(u) := 2 \sum_{t_j \in \pi} \mathbf{1}_{\llbracket x_{t_j \wedge t}, x_{t_{j+1} \wedge t} \rrbracket}(u) |x_{t_{j+1} \wedge t} - u|,$$

then, if f equals the *difference* of two convex functions, we have the following discrete Tanaka-Meyer formula

$$(3.2) \quad f(x_t) - f(x_0) = \sum_{t_j \in \pi} f'_-(x_{t_j})(x_{t_{j+1} \wedge t} - x_{t_j \wedge t}) + \frac{1}{2} \int_{\mathbb{R}} L_t^\pi(u) f''(du).$$

A simple but important remark is that only the values of f in the compact interval $[m_t, M_t]$ are relevant. Note that $L_t^\pi(u) = 0$ for $u \notin [m_t, M_t]$ and $L_t^\pi(\cdot)$ is càdlàg, thus it is bounded; in particular $L_t^\pi(\cdot)$ is f'' -integrable.

In the remainder of this section we will restrict our attention to those functions whose second derivative is not a general Radon measure but instead one which admits a density with respect to the Lebesgue measure. Thus, the underlying measure space will be $\mathbb{R}$ with its Borel sets, endowed with the Lebesgue measure $\mathcal{L}^1(du)$ (sometimes denoted simply by du). We will consider $L_t^{\pi_n}(\cdot)$ as a function in L^p , and denote by $W^{k,p}$ the (Sobolev) space of functions whose k^{th} derivative in the sense of distributions is in L^p ; i.e., $W^{1,p}$ is the set of absolutely continuous functions whose classical derivative (which exists a.e.) belongs to $W^{0,p} = L^p$, and $W^{2,p}$ is the set of C^1 functions whose classical derivative belongs to $W^{1,p}$. The following is our main theorem in this section.

Theorem 3.1. *Let x be continuous function and fix a sequence of partitions $\Pi = (\pi_n)_n$ such that $O_t(x, \pi_n) \rightarrow 0$ as $n \rightarrow \infty$ for all $t \in [0, \infty)$. Then the following are equivalent if $1 < p < \infty$, $q = p/(p-1)$.*

- (1) $\sum_{t_j \in \pi_n} g(x_{t_j})(x_{t_{j+1} \wedge t} - x_{t_j \wedge t})$ converges for every $g \in W^{1,q}$ and $t \in [0, \infty)$ to a continuous function of t , which we denote by $\int_0^t g(x_s) dx_s$.
- (2) $\sum_{t_j \in \pi_n} g(x_{t_j})(x_{t_{j+1} \wedge \cdot} - x_{t_j \wedge \cdot})$ converges uniformly on compacts for every $g \in W^{1,q}$.
- (3) $(L_t^{\pi_n})_n$ converges weakly in L^p to some L_t for all $t \in [0, \infty)$, and $[0, \infty) \ni t \mapsto L_t \in L^p$ is continuous if L^p is endowed with the weak topology.
- (4) For all $t \in [0, \infty)$ there exists $L_t \in L^p$ s.t. $\int_{\mathbb{R}} L_t^{\pi_n}(u) h(u) du \rightarrow \int_{\mathbb{R}} L_t(u) h(u) du$ uniformly on compacts for every $h \in L^q$.
- (5) $x \in \mathcal{Q}^\Pi$ and for all $M \in [0, \infty)$ there exists $t \geq M$ such that $(L_t^{\pi_n})_n$ is bounded in L^p .

If the above conditions are satisfied then $(L_t^{\pi_n})_n$ is bounded in L^p for all $t \in [0, \infty)$, and for all $f \in W^{2,q}$ and $t \in [0, \infty)$

$$(3.3) \quad f(x_t) - f(x_0) = \int_0^t f'(x_s) dx_s + \frac{1}{2} \int_{\mathbb{R}} L_t(u) f''(u) du,$$

and for all Borel bounded h

$$(3.4) \quad \int_0^t h(x_s) d\langle x \rangle_s = \int_{\mathbb{R}} L_t(u) h(u) du.$$

The statements above hold for $p = \infty, q = 1$ if the weak topology on L^p is replaced by the weak* topology on L^∞ . Moreover, they also hold for $p = 1, q = \infty$ if in item 5 boundedness in L^p is replaced by equintegrability.

In Theorem 3.1 we slightly modify⁹ the setting of [28] in order to obtain a stronger theorem with equivalent conditions; the main novelty is that item 5 implies the others. In particular we can exactly describe the difference between functions that only admit (pathwise) quadratic variation and the ones that also have local time. In Example 3.6 below we show that the two notions are strictly different and give an explicit construction of a path which admits quadratic variation but not a pathwise local time.

We will henceforth denote by $\mathcal{L}_p$ the space of continuous functions x for which the equivalent conditions of Theorem 3.1 hold. We will call $L_t(u)$ the *pathwise local time of x at time t at level u* . Observe that $\mathcal{L}_p$ and $L_t(u)$ a priori depend on $\Pi = (\pi_n)_n$, and that $L_t(u)$ depends on x . We will write $\mathcal{L}_p^\Pi$, $L_t^\Pi(u)$, $L_t^x(u)$ or $L_t^{x,\Pi}(u)$ only when we want to highlight this dependences; as in the remainder of this section $\Pi = (\pi_n)_n$ will be fixed, we will never do that, and we will simply write L_t^n for $L_t^{\pi_n}$.

Notice that since $L_t^n(u) = 0$ for $u \notin [m_t, M_t]$, we can consider $L_t^n(u)$ as an element of $L^p(\mu)$ with μ being the restriction of the Lebesgue measure to $[m_t, M_t]$. In particular, Theorem 3.1 hold if $W^{k,q}$ is replaced with $W_{loc}^{k,q}$. Moreover, if $\hat{p} \leq p$, since μ is finite $L^p(\mu)$ embeds continuously in $L^{\hat{p}}(\mu)$, and so $\mathcal{L}_p \subseteq \mathcal{L}_{\hat{p}}$ and the limits of $(L_t^{\pi_n})_n$ in the weak L^p and $L^{\hat{p}}$ topology coincide, so L_t does not really depend on p .

The following is quite a weak convergence result, since we assume even more than the uniform convergence on compacts of g_n to g ; however clearly this result would not hold asking only uniform convergence on compacts. The proposition says in particular that if $x \in \mathcal{L}_p$ the Föllmer integral is a continuous linear functional on

⁹Indeed [28] does not require $t \mapsto L_t$ to be continuous, and considers strong convergence in L^2 instead of weak convergence in L^p .

$W^{1,q}$; this fact could have been used to define Föllmer's integral for $g \in W^{1,q}$ as the continuous extension of the Föllmer's integral for $g \in C^1$ defined in Theorem 2.5, as done in [3].

Proposition 3.2. *Let $p \in (1, \infty]$ (resp. $p = 1$) with conjugate exponent q . If $x \in \mathcal{L}_p$, $g_n, g \in W^{1,q}$, $g_n(x_0) \rightarrow g(x_0)$ and $g'_n \rightarrow g'$ in the weak (resp. weak*) topology of L^q , then $\int_0^t g_n(x_s) dx_s \rightarrow \int_0^t g(x_s) dx_s$ for all $t \in [0, \infty)$, and the convergence is uniform on compacts if moreover $|g'_n| \rightarrow |g'|$ weakly (resp. weakly*) in L^q .*

Proof. Define $f(u) := \int_{x_0}^u g(y) dy$ and analogously f_n from g_n , and notice that $f_n(u) \rightarrow f(u)$ for all $u \in \mathbb{R}$, so Tanaka-Meyer formula (3.3) gives the thesis. If moreover $|g'_n| \rightarrow |g'|$ weakly in L^q then since the positive part $\max(h, 0)$ of h equals $(h + |h|)/2$, Polya's scholium 2.2 shows local uniformity of the convergence

$$\int_{\mathbb{R}} L_t(u) \max(g'_n(u), 0) du \rightarrow \int_{\mathbb{R}} L_t(u) \max(g'(u), 0) du;$$

working analogously with the negative parts we get the thesis. $\square$

In the rest of this section we establish Theorem 3.1 via a series of lemmas; if not explicitly stated otherwise, p is assumed to be in $(1, \infty)$.

Lemma 3.3. *$x \in \mathcal{Q}$ iff $\int_{\mathbb{R}} L_t^n(u) du$ converges to a continuous function ψ_t of $t \in [0, \infty)$. In this case the convergence is uniform on compacts and $\langle x \rangle = \psi$.*

Proof. Applying formula (3.2) with $f(x) = x^2 \in L^1([m_t, M_t])$ we obtain

$$(3.5) \quad \sum_{t_j \in \pi_n} x_{t_{j+1} \wedge t}^2 - x_{t_j \wedge t}^2 - 2x_{t_j}(x_{t_{j+1} \wedge t} - x_{t_j \wedge t}) = \int_{\mathbb{R}} L_t^n(u) du$$

The statement follows rewriting the left side of (3.5) as $\sum_{t_j \in \pi_n} (x_{t_{j+1} \wedge t} - x_{t_j \wedge t})^2$. $\square$

Given $x \in \mathcal{Q}^\Pi$, ν_t will denote the *occupation measure* of $(x_s)_{s \leq t}$ along Π , defined on the Borel sets of $[0, t]$ by $\nu_t(A) := \int_0^t 1_A(x_s) d\langle x \rangle_s^\Pi$.

Lemma 3.4. *If $x \in \mathcal{Q}$ and $t \in [0, \infty)$ the following are equivalent.*

(1) *For every $g \in W^{1,q}$ the following sequence converges*

$$(3.6) \quad \sum_{t_j \in \pi_n} g(x_{t_j})(x_{t_{j+1} \wedge t} - x_{t_j \wedge t}).$$

(2) *The sequence $(L_t^n(\cdot))_n$ converges in the weak topology of L^p (to a quantity which we denote by $L_t(\cdot)$).*

The above conditions imply that $(L_t^n(\cdot))_n$ is bounded in L^p and (3.3) holds. Conversely, if $(L_t^n(\cdot))_n$ is bounded in L^p and $x \in \mathcal{Q}$ then items (1) and (2) hold, and ν_t has a density L_t with respect to $\mathcal{L}^1$.

Proof. The equivalence between items (1) and (2), and the fact that these imply (3.3), follows immediately applying (3.2) with $f(u) := \int_{x_*}^u g(y) dy$. That item (2) implies the boundedness of $(L_t^n(\cdot))_n$ follows from Banach-Steinhaus Theorem. For the opposite implication notice that since $x \in \mathcal{Q}$ we can use Theorem 2.5, which together with (3.2) shows that

$$(3.7) \quad \exists \lim_n \int_{\mathbb{R}} L_t^n(u) h(u) du = \int_0^t h(x_s) d\langle x \rangle_s = \int h d\nu_t \quad \text{for all } h \in C^0.$$

Since L^p is reflexive (see [6, Theorem 4.10]), its unit ball is sequentially compact in the weak topology [6, Theorem 3.18], so we can get convergence of L_t^n along some subsequence (of any subsequence) to some L_t and all we have to show is that the limit does not depend on the subsequence. Considering $(L_t^n)_n$ as elements of the measure space $([m_t, M_t], \mathcal{L}^1)$ we have that $C^0 \subseteq L^p$, so $\int g(u) \nu_t(du) = \int g(u) L_t(u) du$ for all

continuous g . Thus $L_t(u)du = \nu_t(du)$; in particular the limit L_t does not depend on the subsequence, proving item (2). $\square$

Lemma 3.5. *If the equivalent conditions 1 and 2 of Lemma 3.4 are satisfied for all $t \in [0, \infty)$, the following conditions are equivalent.*

- (1) *For every $g \in W^{1,q}$ the function $\int_0^t g(x_s)dx_s$ is continuous in $t \in [0, \infty)$.*
- (2) *For every $g \in W^{1,q}$ the convergence in (3.6) is uniform on compacts.*
- (3) *The map $[0, \infty) \ni t \mapsto L_t(\cdot) \in L^p$ is continuous in the weak topology of L^p .*
- (4) *For every $h \in L^q$ the convergence $\int_{\mathbb{R}} L_t^n(u)h(u)du \rightarrow \int_{\mathbb{R}} L_t(u)h(u)du$ is uniform on compacts.*

Proof. The identity (3.2) shows that items (2) and (4) are equivalent. The identity (3.3) shows that (1) and (3) are equivalent. Trivially item (2) implies item (1). Finally scholium 2.2 shows that item (3) implies item (4). $\square$

Proof of Theorem 3.1. If item 5 holds, since the last term in the decomposition (4.3) is bounded by $O_t(x, \pi)$ and the two sums are increasing in t , $(L_t^n)_n$ is bounded in L^p for all $t \in [0, \infty)$; moreover Lemma 3.4 shows that for all $h \in L^q$

$$(3.8) \quad \exists \lim_n \int_{\mathbb{R}} L_t^n(u)h(u)du = \int L_t(u)h(u)du = \int h d\nu_t = \int_0^t h(x_s)d\langle x \rangle_s;$$

Since (3.8) shows that $\int L_t(u)h(u)du$ is a continuous function of t , Lemma 3.5 implies that item 3 holds. That item 3 implies $x \in \mathcal{Q}$ follows applying Lemma 3.3 since $\mathbf{1}_{[m_t, M_t]} \in L^p$ and $L_t^n = 0$ outside $[m_t, M_t]$. Lemma 3.4 states that ν_t has a density L_t ; thus, formula (3.4) holds. All other assertions follow directly from Lemmas 3.4 and 3.5.

If $p = 1$ or $p = \infty$ the proofs hold with the following minor modification in the part of the proof of Lemma 3.4 which deals with the sequential compactness of $(L_t^n)_n$. If $p = \infty$, the unit ball of L^∞ is sequentially compact since it is compact (and metrizable) in the weak* topology because of Banach-Alaoglu Theorem (resp. since L^1 is separable), see [6, Theorem 3.16] (resp. see [6, Theorems 3.28 and 4.13]). If $p = 1$, since $L_t^n \geq 0$, Lemma 3.3 implies that $(L_t^n)_n$ is bounded in L^1 , so if $(L_t^n)_n$ is equintegrable then it is weakly sequentially compact (by the Dunford-Pettis Theorem, see [6, Theorem 4.30]). $\square$

We end this section with the following

Example 3.6. *There exists a function that admits pathwise quadratic variation but no pathwise local time.*

Put differently, we show that the inclusion $\mathcal{L}_1^\Pi \subset \mathcal{Q}^\Pi$ can be strict. This proves that the additional requirement in (5) in Theorem 3.1 is not automatic and is indeed needed. More precisely, we now construct a continuous function $x : [0, 1] \rightarrow \mathbb{R}$ and a sequence of refining partitions $\Pi = (\pi_n)_n$ of $[0, 1]$ whose mesh is going to zero and such that $\langle x \rangle_t^{\pi_n}$ converges for all t to the (continuous!) Cantor function $c(t)$ (a.k.a. the Devil staircase) but $(L_1^{\pi_n})_n$ does not converge weakly in $L^1(du)$; in particular x has no pathwise local time along $(\pi_n)_n$, no matter which definition we use¹⁰. Our construction was inspired by a remark by Bertoin on page 194 of [3].

Divide $[0, 1]$ into three equal subintervals and remove the middle one $I_1^1 := (\frac{1}{3}, \frac{2}{3})$. Divide each of the two remaining closed intervals $[0, \frac{1}{3}]$ and $[\frac{2}{3}, 1]$ into three equal

¹⁰Meaning that if one replaced the weak topology of L^1 with any stronger topology (e.g. the weak/strong topology of L^p , or the uniform topology as done in [20, Definition 2.5]) one would still not obtain convergence of $L_t^{\pi_n}$.

subintervals and remove the middle ones $I_1^2 := (\frac{1}{3^2}, \frac{2}{3^2})$ and $I_2^2 := (\frac{7}{3^2}, \frac{8}{3^2})$. Continuing in this fashion, at each step i we remove the middle intervals $I_1^i, \dots, I_{2^{i-1}}^i$, each of length $1/3^i$. The Cantor set is defined as

$$C := [0, 1] \setminus \bigcup_{i=1}^{\infty} \bigcup_{j=1}^{2^{i-1}} I_j^i,$$

and the function which we will consider is $x(t) := \sqrt{2 \min_{s \in C} |s - t|}$. To construct our partitions π_n of $[0, 1]$ we define first a refining sequence $(\pi_{n,j}^i)_n$ of Lebesgue partitions of I_j^i setting $\pi_{n,j}^i = (t_{n,j}^{k,i})_{k=0}^{2^{ni+1}}$ with $t_{n,j}^{0,i} = \inf I_j^i$ (so that $x(t_{n,j}^{0,i}) = 0$), and

$$(3.9) \quad t_{n,j}^{k+1,i} := \inf\{t > t_{n,j}^{k,i} : x_t \in (2^{-ni} \sup_{t \in I_j^i} x(t))\mathbb{Z}, x_t \neq x_{t_{n,j}^{k,i}}\},$$

so that $t_{n,j}^{2^{ni+1},i} = \sup I_j^i$ and $|x_{t_{n,j}^{k+1,i}} - x_{t_{n,j}^{k,i}}| = 2^{-ni} \sup_{t \in I_j^i} x(t) = 1/(\sqrt{3}2^n)^i$ and so

$$(3.10) \quad \langle x \rangle_{I_j^i}^{\pi_{n,j}^i} := \sum_{k=0}^{2^{ni+1}-1} (x_{t_{n,j}^{k+1,i}} - x_{t_{n,j}^{k,i}})^2 = 2^{ni+1} 3^{-i} 2^{-2ni} = 3^{-i} 2^{1-ni}.$$

Then define our refining sequence $(\pi_n)_n$ of partitions of $[0, 1]$ whose mesh is going to zero setting $\pi_n := \{0, 1\} \cup \bigcup_{i=1}^n \bigcup_{j=1}^{2^{i-1}} \pi_{n,j}^i$, so that as $n \rightarrow \infty$

$$(3.11) \quad \langle x \rangle_1^{\pi_n} = \sum_{i=1}^n \sum_{j=1}^{2^{i-1}} \langle x \rangle_{I_j^i}^{\pi_{n,j}^i} = \sum_{i=1}^n \left(\frac{2}{2^n 3}\right)^i = (1 - (\frac{2}{2^n 3})^{n+1}) / (1 - (\frac{2}{2^n 3})) \rightarrow 1.$$

Now, the Cantor function c is defined on $[0, 1]$ to be the only¹¹ continuous extension of the function f which is defined on the set $D := \{0, 1\} \cup \bigcup_{i=1}^{\infty} \bigcup_{j=1}^{2^{i-1}} \bar{I}_j^i$ in this way: $f(0) = 0, f(1) = 1$, and each time we remove the middle third I_j^i from a parent interval J_j^i , f is defined on the closure $\bar{I}_j^i$ of I_j^i to be the average of its values at the extremes of J_j^i (so $f = 1/2$ on $\bar{I}_1^1$, $f = 1/4$ on $\bar{I}_1^2$ and $f = 3/4$ on $\bar{I}_2^2$ etc.).

Since the difference between $\langle x \rangle_t^{\pi_n}$ and the increasing function $\sum_{\pi_n \ni t_j \leq t} (x_{t_{j+1}} - x_{t_j})^2$ is going to zero for all t as $n \rightarrow \infty$, and since c is continuous and increasing, to conclude that $\langle x \rangle_t^{\pi_n} \rightarrow c(t)$ for all t it is enough to show it for all t in the dense set D . We already know this for $t = 1$ and (trivially) for $t = 0$. Since $\langle x \rangle_{(0, \frac{1}{3}]}^{\pi_n} = \langle x \rangle_{(\frac{2}{3}, 1]}^{\pi_n}$, and (3.10) shows that $\langle x \rangle_{(\frac{1}{3}, \frac{2}{3}]}^{\pi_n} \rightarrow 0$, (3.11) and (2.6) give that $\langle x \rangle_t^{\pi_n} \rightarrow 1/2 = c(t)$ for all $t \in [\frac{1}{3}, \frac{2}{3}] = \bar{I}_1^1$. Analogously $\langle x \rangle_{(0, \frac{1}{9}]}^{\pi_n} = \langle x \rangle_{(\frac{2}{9}, \frac{1}{3}]}^{\pi_n}$, and (3.10) shows that $\langle x \rangle_{(\frac{1}{9}, \frac{2}{9}]}^{\pi_n} \rightarrow 0$, so $\langle x \rangle_{\frac{1}{3}}^{\pi_n} \rightarrow 1/2$ and (2.6) give that $\langle x \rangle_t^{\pi_n} \rightarrow 1/2^2 = c(t)$ for all $t \in [\frac{1}{9}, \frac{2}{9}] = \bar{I}_1^2$. In this way we see that $\langle x \rangle_t^{\pi_n} \rightarrow c(t)$ for all $t \in D$ and thus for all $t \in [0, 1]$.

To conclude, let us prove that the pathwise local time $L_1^{\pi_n}(u)$ converges to 0 for all $u \neq 0$, so that $(L_1^{\pi_n})_n$ does not converge weakly in $L^1(du)$ (because otherwise, by the Dunford-Pettis Theorem [6, Theorem 4.30], it would be uniformly integrable and would thus converge to zero strongly in $L^1(du)$, whereas we know that $\int_0^1 L_1^{\pi_n}(u) du = \langle x \rangle_1^{\pi_n} \rightarrow c(1) = 1$). Since $x(t) \geq 0$ for all t , $L_1^{\pi_n}(u) = 0$ for all n if $u < 0$. For each i, j the function $(x(t))_{t \in \pi_n \cap I_j^i}$ crosses¹² each level $u > 0$ at most twice, and since $\sup\{x(t) : t \notin \bigcup_{i=1}^k \bigcup_{j=1}^{2^{i-1}} I_j^i\} = 1/\sqrt{3^{k+1}}$ is strictly smaller than any $u > 0$ for big enough $i = i(u)$, the number of times $(x(t))_{t \in \pi_n}$ crosses level $u > 0$ is bounded above independently of n ; since $O_1(x, \pi_n) = 1/(\sqrt{3}n) \rightarrow 0$ as $n \rightarrow \infty$, this implies that $L_1^{\pi_n}(u) \rightarrow 0$.

¹¹Such extension exists and is unique since f is continuous and D is dense in $[0, 1]$.

¹²Meaning that either $x_{t_k} \leq u < x_{t_{k+1}}$ or $x_{t_{k+1}} \leq u < x_{t_k}$ where $(t_k)_k := \pi_n \cap I_j^i$.

4. CHANGE OF VARIABLES AND TIME-CHANGE

In applications to the study of variance derivatives, for example [8], one starts with a continuous positive price function S , and the ‘variance’ is defined as the quadratic variation of the *log price* $x = \log S$. In this connection it is useful to be able to change variables, and to relate for example the local time of $\log(x)$ with the one of x . We recall that, although being a semimartingale is preserved only by C^2 transformations, possessing a quadratic variation (in the sense of Definition 2.1) is more generally invariant under C^1 transformations; indeed $f \in C^1$ and $x \in \mathcal{Q}^\Pi$ imply $f(x) \in \mathcal{Q}^\Pi$ and $\langle f(x) \rangle_t^\Pi = \int_0^t f'(x_s)^2 \langle x \rangle_s^\Pi$ (see [24, Proposition 2.2.10]). We prove below a similar result for the pathwise local time (if f is monotone), extending the C^2 case treated in [8]; then we show that time-change preserves the pathwise local time.

For Propositions 4.1 and 4.2 we consider a fixed sequence of partition $(\pi_n)_n$ such that $O_t(x, \pi_n) \rightarrow 0$ as $n \rightarrow \infty$ for all $t \in [0, \infty)$.

Proposition 4.1. *Let $x \in \mathcal{L}_p$ and let $f : \mathbb{R} \rightarrow \mathbb{R}$ be C^1 and strictly monotone. Then $f(x) \in \mathcal{L}_p$ and the pathwise local times of x and $f(x)$ are related by*

$$(4.1) \quad L_t^{f(x)}(f(u)) = |f'(u)| L_t^x(u).$$

In Proposition 4.1 one considers the same sequence of partitions $(\pi_n)_n$ for x and for $f(x)$. This seems to be problematic, since ideally we would like Proposition 4.1 to hold also for Lebesgue partitions, and clearly if P is a partition of $\mathbb{R}$ then $\pi_P(f(x))$ differs from $\pi_P(x)$. However Proposition 4.1 does apply to suitably chosen Lebesgue partitions since $\pi_{f(P)}(f(x)) = \pi_P(x)$ if f is strictly increasing.

To prove Proposition 4.1 and better understand the behavior of L^π , let $t_J := \max\{t_j \in \pi : t_j \leq t\}$ and

$$(4.2) \quad \begin{aligned} \pi_t^U(u) &:= \{t_j \in \pi : x_{t_j} \leq u < x_{t_{j+1}}, t_{j+1} \leq t\}, \\ \pi_t^D(u) &:= \{t_j \in \pi : x_{t_{j+1}} \leq u < x_{t_j}, t_{j+1} \leq t\}, \end{aligned}$$

and notice that, since all the terms in (3.1) with $t < t_j$ are equal to zero,

$$(4.3) \quad L_t^\pi(u)/2 = \sum_{t_j \in \pi_t^U(u)} (x_{t_{j+1}} - u) + \sum_{t_j \in \pi_t^D(u)} (u - x_{t_{j+1}}) + \mathbf{1}_{[x_{t_J}, x_t)}(u) |x_t - u|.$$

Proof of Proposition 4.1. Since adding t to any partition π does not change the value of $L_t^\pi(u)$ and insures that the last term in (4.3) is zero, we assume without loss of generality that our partitions contain t . If f is strictly increasing and $a \leq b$ then

$$x_a \leq u < x_b \text{ iff } f(x_a) \leq f(u) < f(x_b),$$

and thus (4.3) implies that $L_t^{f(x), \pi}(u)/2$ equals

$$(4.4) \quad \sum_{t_j \in \pi_t^U(u)} (f(x_{t_{j+1}}) - f(u)) + \sum_{t_j \in \pi_t^D(u)} (f(u) - f(x_{t_{j+1}})).$$

If $t_j \in \pi_t^U(u)$, since $f \in C^1$ there exists $z_j(u) \in (u, x_{t_{j+1}})$ such that

$$f(x_{t_{j+1}}) - f(u) = f'(z_j(u))(x_{t_{j+1}} - u),$$

so we can write the first sum in (4.4) as

$$(4.5) \quad \sum_{t_j \in \pi_t^U(u)} (f'(z_j(u)) - f'(u))(x_{t_{j+1}} - u) + f'(u) \sum_{t_j \in \pi_t^U(u)} (x_{t_{j+1}} - u).$$

Treating analogously the second sum in (4.4) we get that

$$(4.6) \quad L_t^{f(x), \pi}(u) - f'(u) L_t^{x, \pi}(u)$$

is bounded by

$$(4.7) \quad 2 \sum_{t_j \in \pi_t^U(u) \cup \pi_t^D(u)} |f'(z_j(u)) - f'(u)| |x_{t_{j+1}} - u|.$$

Now define

$$(4.8) \quad R_t(g, \pi) := \max\{|g(c) - g(d)| : c, d \in [m_t, M_t], |c - d| \leq O_t(x, \pi)\}.$$

Clearly (4.7) with $\pi = \pi_n$ is bounded by $R_t(f', \pi_n) L_t^{x, \pi_n}(u)$, so since L_t^{x, π_n} converges to L_t^x and $R_t(f', \pi_n) \rightarrow 0$ we get that (4.6) with $\pi = \pi_n$ converges to 0, proving the thesis.

If f is strictly decreasing then the argument is the same save for the sign change, which comes from the fact that upcrossings are now transformed in downcrossings and conversely, so $x_{t_{j+1}} - u$ needs to be replaced by $u - x_{t_{j+1}}$. $\square$

Proposition 4.2. *Let $\tau : [0, \infty) \rightarrow [0, \infty)$ be an increasing càdlàg function such that x_τ is continuous and $\tau(0) = 0$. Given $\Pi = (\pi_n)_n$, let $\tau(\Pi) := (\tau_{\pi_n})_n$ where, given $\pi = (t_j)_j$, τ_π denotes the partition $(\tau_{t_j})_j$. If $O_{\tau_t}(x, \tau_{\pi_n}) \rightarrow 0$ for all $t \in [0, \infty)$ and $x \in \mathcal{L}_p^{\tau(\Pi)}$ then $O_t(x_\tau, \pi_n) \rightarrow 0$ for all $t \in [0, \infty)$, $x_\tau \in \mathcal{L}_p^\Pi$ and the pathwise local times are related by*

$$L_t^{x_\tau, \Pi}(u) = L_{\tau_t}^{x, \tau(\Pi)}(u).$$

Moreover if τ is bijective¹³ then x_τ is continuous, $O_{\tau_t^{-1}}(x_\tau, \tau_\pi^{-1}) = O_t(x, \pi)$ for any partition π , and if P is a partition of $\mathbb{R}$ then the Lebesgue partitions of x_τ and x satisfy $\pi_P(x_\tau) = \tau_{\pi_P(x)}^{-1}$.

Proof. Even if τ is not strictly increasing, the identity

$$\{\tau_s : s \in [t_i, t_{i+1}) \cap [0, t]\} = [\tau_{t_i}, \tau_{t_{i+1}}) \cap [0, \tau_t] \cap \tau([0, \infty)),$$

holds, and it trivially implies that $O_t(x_\tau, \pi_n) \leq O_{\tau_t}(x, \tau_{\pi_n})$, with equality if τ is a bijection. Trivially $L_t^{x_\tau, \pi}(u) = L_{\tau_t}^{x, \tau_\pi}(u)$ holds for every partition π , and everything else follows easily. $\square$

Note that Propositions 4.1 and 4.2 hold (with the same proof) with other definitions of existence of the pathwise local time; for example if one replaced the weak topology of L^p for $p \in [1, \infty)$ (resp. the weak* topology on L^∞) with the strong one in item 3 of Theorem 3.1, or if one considered Definition 2.5 in [20].

5. EXTENSION TO CONVEX FUNCTIONS

The choice of how to define the existence of the pathwise local time is intrinsically linked to the class of functions for which one is able to establish the pathwise Tanaka-Meyer formula (3.3). To establish it for all convex functions one needs to restrict significantly the set of paths for which the local time exists; nonetheless, in [20] it is shown that this approach works for general enough paths (namely, for the ‘typical price path’ in the sense of Vovk [27]).

It is natural to ask if the above can be extended even further, to all continuous functions. As already remarked in [11], the next proposition shows that, if one wants to consider the generic path of a local martingales, the answer is no – to define stochastic integrals in a pathwise manner for more general integrands one has to consider partitions which depend both on the integrator and the integrand as in [4, Theorem 7.14] and [14].

¹³I.e. if τ is strictly increasing, continuous and such that $\tau(0) = 0, \lim_{t \rightarrow \infty} \tau(t) = \infty$.

Proposition 5.1. (*Stricker [25]*) *Let $x \in C[0, T]$. If for every bounded continuous function f on $\mathbb{R}$ the Riemann sums $\sum_i f(x_{t_i})(x_{t_{i+1}} - x_{t_i})$ converge as the mesh size tends to 0, then x has finite variation.*

In what follows we take a different route from [20] to further extend Föllmer's integral and Tanaka-Meyer formula from $f \in C^2$ to f which is a difference of convex functions. In a way somewhat reminiscent of [3, Proposition 1.2], we do this defining $\int_0^t f'_-(x_s)dx_s$ as the limit of $\int_0^t f'_n(x_s)dx_s$, where f_n are C^2 functions converging to f and $\int_0^t f'_n(x_s)dx_s$ is defined in Theorem 2.5 as a limit of Riemann sums.

We now fix $\Pi = (\pi_n)_n$ such that $O_t(x, \pi_n) \rightarrow 0$ as $n \rightarrow \infty$ for all $t \in [0, \infty)$, and we consider a function g which is C^2 , positive and with compact support in $[0, \infty)$, and such that $\int_{\mathbb{R}} g(x)dx = 1$. We will then approximate the target function f with $f_n := g_n * f$, where $*$ denotes the convolution between a function and a measure (or a function), g_n is the mollifier $g_n(u) := ng(nu)$ and f'' is the second distributional derivative of f . Recall that, if $x \in \mathcal{L}_1$, $L_t(\cdot)$ is seen an element of $L^1(du)$; the following theorem assumes that there exists a modification of L_t which is càdlàg in u , i.e., a function $\tilde{L}_t(u)$ càdlàg in u and such that, for each t , the set $\{u : \tilde{L}_t(u) \neq L_t(u)\}$ has zero Lebesgue measure; this is not an unreasonable assumption, as it is satisfied by a.e. path of a semimartingale (indeed the local time of a continuous semimartingale has a modification which is jointly càdlàg in u and continuous in t).

Theorem 5.2. *Assume that $x \in \mathcal{L}_1$ and there exists a modification $L_t(u)$ of the pathwise local time which is càdlàg in u for all t . If f is convex then f_n is C^2 and for all $t \in [0, \infty)$ the Föllmer integral $\int_0^t f'_n(x_s)dx_s$ converges to a finite limit, denoted by $\int_0^t f'_-(x_s)dx_s$, which independent of the choice of g and satisfies*

$$(5.1) \quad f(x_t) - f(x_0) = \int_0^t f'_-(x_s)dx_s + \frac{1}{2} \int_{\mathbb{R}} L_t(u) f''(du).$$

Moreover if $L_t(u)$ is jointly càdlàg in u and continuous in t then the convergence is uniform on compacts and $t \mapsto \int_0^t f'_-(x_s)dx_s$ is continuous.

Theorem 5.2 allows to define ¹⁴ $\int_0^t g_-(x_s)dx_s$ for any function g of finite variation on compacts, since then $f(u) := \int_{x_0}^u g(y)dy$ is the difference of convex functions. We now study the continuity properties of $g \mapsto \int_0^t g_-(x_s)dx_s$.

Proposition 5.3. *Let $x \in \mathcal{L}_1$ and assume that there exists a modification $L_t(u)$ of the pathwise local time which is continuous in u . If g_n , and g are functions of finite variation on compacts, $g_n(x_0) \rightarrow g(x_0)$ and $g'_n \rightarrow g'$ weakly (in the topology of measures), then $\int_0^t g_n(x_s)dx_s \rightarrow \int_0^t g(x_s)dx_s$ for all $t \in [0, \infty)$, and the convergence is uniform on compacts if moreover $|g'_n| \rightarrow |g'|$ weakly.*

Proof. Define $f(u) := \int_{x_0}^u g(y)dy$ and analogously f_n from g_n , and notice that $f_n(u) \rightarrow f(u)$ for all $u \in \mathbb{R}$, so Tanaka-Meyer formula (5.1) gives the thesis. If moreover $|g'_n| \rightarrow |g'|$ weakly then, since the positive part $\max(h, 0)$ of h equals $(h + |h|)/2$, Polya's scholium 2.2 shows local uniformity of the convergence

$$\int_{\mathbb{R}} L_t(u) \max(g'_n, 0)(du) \rightarrow \int_{\mathbb{R}} L_t(u) \max(g', 0)(du);$$

¹⁴As pointed out to us by Föllmer [10] another possible definition of $\int_0^t f'_-(x_s)dx_s$ for non-smooth convex f is as the limit of $\int_0^t f'_k(x_s)dx_s$ for any $(f_k)_k \subseteq C^2$ such that $f'_k(x)dx$ (considered as a measure) converges weakly to $f''(x)dx$. It follows from (3.3) that this definition makes sense (i.e. the limit exists and is independent of the approximating sequence $(f_k)_k$) if $L_t(u)$ has a modification which is continuous in u).

working analogously with the negative parts we get the thesis. $\square$

It is then natural to ask for which paths the above given definition of $\int_0^t f'_-(x_s)dx_s$ coincides with the one used in Theorem 3.1 for $f \in W^{2,q}$. The answer is that the limit of the Riemann sums $\sum_{t_j \in \pi_n} f'_-(x_{t_j})(x_{t_{j+1} \wedge t} - x_{t_j \wedge t})$ exists and equals $\int_0^t f'_-(x_s)dx_s$ iff $\int L_t^{x, \pi_n}(u)f''(du)$ converges to $\int L_t^x(u)f''(du)$, as it follows from (3.2) and (5.1). In particular this holds if $x \in \mathcal{L}_p \subseteq \mathcal{L}_1$, so the definition of the Föllmer's integral given in Theorem 5.2 is indeed an extension of the one given in Theorem 3.1.

Proof of Theorem 5.2. Since f is uniformly continuous on compacts, $f_n \rightarrow f$ pointwise. Thus, if we can prove that $\int_{\mathbb{R}} L_t df_n'' \rightarrow \int_{\mathbb{R}} L_t df''$, the thesis follows applying (3.3) to f_n and taking limits; indeed (5.1) shows that $\int_0^t f'_-(x_s)dx_s$ does not depend on g . Define $\hat{g}_n(u) := g_n(-u)$ and apply Fubini's theorem and the identity $f_n'' = g_n * f''$ to get that

$$(5.2) \quad \int_{\mathbb{R}} L_t df_n'' = \int_{\mathbb{R}} (\hat{g}_n * L_t) df''.$$

Since L_t is zero outside $[m_t, M_t]$ and g has compact support, L_t, g and $\hat{g}_n * L_t$ are all 0 outside a common compact interval $[-A, A]$. In particular since $L_t(\cdot)$ is càdlàg it is bounded; since $\sup_u |\hat{g}_n * L_t(u)| \leq \sup_u |L_t(u)|$, the thesis follows from the dominated convergence theorem and (5.2) if we prove that $\hat{g}_n * L_t(u) \rightarrow L_t(u)$ for all u . Notice that

$$(5.3) \quad (\hat{g}_n * L_t - L_t)(u) = \int_{\mathbb{R}} \hat{g}_n(y)(L_t(u-y) - L_t(u))dy.$$

Since $L_t(\cdot)$ is right continuous, for every $\epsilon > 0$ and u there is an n such that

$$(5.4) \quad |L_t(u-y) - L_t(u)| < \epsilon \text{ if } y \in [-A/n, 0];$$

since $g = 0$ outside $[0, A]$, the integral on the right side of (5.3) is actually over $[-A/n, 0]$, so $|\hat{g}_n * L_t(u) - L_t(u)| < \epsilon$.

Finally if $L_t(u)$ is jointly càdlàg in u and continuous in t then n such that (5.4) holds can be chosen as to hold simultaneously for all t in any given compact set. This implies that the convergence is uniform on compacts, and so $\int_0^t f'_-(x_s)dx_s$ is continuous. $\square$

Remark 5.4. If $x \in \mathcal{L}^\Pi$ then the pathwise local time $(L_t)_t$ has a càdlàg increasing modification $(l_t)_t$, and for all Borel bounded h

$$(5.5) \quad \int_0^T h(t, x_t) d\langle x \rangle_t = \int_{\mathbb{R}} \int_0^T h(t, u) dl_t(u) du$$

6. UPCROSSING REPRESENTATIONS OF LOCAL TIME

In this section we will consider a continuous semimartingale $X = (X_t)_t$ (with $t \in [0, \infty)$ or $t \in [0, T]$) with canonical semimartingale decomposition $X = M + V$ and with (classical) local time $\ell_t(u)$ which is jointly continuous in t and càdlàg in u (such a version exists, see [15, Chapter 3, Theorem 7.1]). We recall that ℓ is jointly continuous if X is a local martingale (under the original probability $\mathbb{P}$ or a dominating one, i.e. a $\mathbb{Q}$ such that $\mathbb{P} \ll \mathbb{Q}$), see [22, Chapter 6, Theorem 1.7].

The following is the main theorem of this section; it essentially says that the pathwise local time sampled along optional partitions $(\pi_n)_n$ exists on a.e. path of a semimartingale, and that a.e. it does not depend on $(\pi_n)_n$.

Theorem 6.1. *Assume that $f : \mathbb{R} \rightarrow \mathbb{R}$ equals the difference of two convex functions, that π_n are optional partitions such that $O_T(X, \pi_n) \rightarrow 0$ a.s. and that $X = (X_t)_{t \in [0, \infty)}$ is a continuous semimartingale. If X has a jointly continuous local time ℓ , or if f is C^1 , then there exists a subsequence $(n_k)_k$ such that, for ω outside a $\mathbb{P}$ -null set (which may depend on f'')*

$$(6.1) \quad \sup_{t \leq T} \left| L_t^{X(\omega), \pi_{n_k}(\omega)}(u) - \ell_t(\omega, u) \right| \rightarrow 0 \quad \text{in } L^p(|f''|(du)) \text{ as } k \rightarrow \infty$$

simultaneously for all $p \in [1, \infty)$, $T < \infty$.

Note that applying Theorem 6.1 with $f(x) = x^2/2 \in C^1$ gives in particular that a.e. path of a continuous semimartingale is in $\mathcal{L}_p$ for all $p < \infty$; indeed, $L_t^{X, \pi_{n_k}}(u) \rightarrow \ell_t(u)$ strongly (and thus weakly) in $L^p(dx)$ a.s. for all t .

The previous theorem follows from the following technical statement.

Theorem 6.2. *Let π_n be optional partitions such that $O_T(X, \pi_n) \rightarrow 0$ a.s., $X \in \mathcal{S}^p$ and define*

$$(6.2) \quad h^{\pi_n}(u) := \left\| \sup_{t \leq T} \left| L_t^{X(\omega), \pi_n(\omega)}(u) - \ell_t(\omega, u) \right| \right\|_{L^p(\mathbb{P}(d\omega))}, \quad u \in \mathbb{R}.$$

Then $h^{\pi_n}(\cdot)$ is bounded and $(h^{\pi_n}(\cdot))_n$ converges pointwise (resp. μ a.e.) to 0 if ℓ is jointly continuous (resp. if μ is a measure with no atoms).

In the special case where π_n is the Lebesgue partition π_{P_n} (for some partition P_n of $\mathbb{R}$), Theorem 6.2 closely relates to the downcrossing representation of local time conjectured by Lévy (proved by Itô and McKean for Brownian motion and extended by El Karoui to semimartingales) found in [22, Theorem VI.1.10]. Indeed, as we explain below, Lévy's representation is equivalent to the following fact: if $X \in \mathcal{S}^p$ and $0 \in P_n$ for all n then $h^{\pi_n}(0) \rightarrow 0$. Note that one can not deduce $h^{\pi_n}(u) \rightarrow 0$ for general u from the case $u = 0$: indeed even if trivially $L_t^{x, \pi_P}(u) = L_t^{x-u, \pi_P-u}(0)$ and the local time ℓ^X of a semimartingale X satisfies $\ell_t^X(u) = \ell_t^{X-u}(0)$, in general $0 \notin P_n - u$.

Let us show the equivalence between [22, Theorem VI.1.10] and $h^{\pi_n}(0) \rightarrow 0$ in the notationally simpler case of the partitions $\pi_{\epsilon\mathbb{Z}}$, where $\epsilon\mathbb{Z} := (\epsilon k)_{k \in \mathbb{Z}}$; however this equivalence (and [22, Theorem VI.1.10]) hold with the same proof in full generality¹⁵. Given a continuous path $x = (x_s)_{s \leq t}$ and $a < b$, we set $\sigma_0^{a,b} := 0$, $\tau_0^{a,b} = \inf\{t : x_t = b\}$ and, for $k \geq 1$,

$$(6.3) \quad \sigma_k^{a,b} := \inf\{t > \tau_{k-1}^{a,b} : x_t = a\}, \quad \tau_k^{a,b} := \inf\{t > \sigma_k^{a,b} : x_t = b\}.$$

It turns out that the downcrossings $D_t^\epsilon(u) := \max\{k : \sigma_k^{u, u+\epsilon} \leq t\}$ of $(X_s)_{s \leq t}$ from $u + \epsilon$ to u are closely related to the local time along $\pi_{\epsilon\mathbb{Z}}$. Indeed, the upcrossings $U_t^\epsilon(u) := \max\{k : \tau_k^{u+\epsilon, u} \leq t\}$ of $(X_s)_{s \leq t}$ from u to $u + \epsilon$ differ from $D_t^\epsilon(u)$ by at most 1, so if given P partition of $\mathbb{R}$ we set

$$(6.4) \quad \underline{P}(u) := \max\{p_k \in P : p_k \leq u\}, \quad \overline{P}(u) := \min\{p_k \in P : u < p_k\},$$

using (4.3) we get that $L_t^{\pi_P}(u)/2$ equals

$$(6.5) \quad U_t^{\pi_P}(u)(\overline{P}(u) - u) + D_t^{\pi_P}(u)(u - \underline{P}(u)) + \mathbf{1}_{[x_{t_J}, x_t)}(u)|x_t - u|.$$

¹⁵Meaning for all π_{P_n} corresponding to P_n partitions of $\mathbb{R}$ whose step converges to zero and such that $0 \in P_n$ for all n .

Thus, since the last term in (6.5) is bounded by $O_t(x, \pi_P) \leq \|P\|$, we get that

$$(6.6) \quad |L_t^{\pi_{\epsilon\mathbb{Z}}}(u)/2 - \epsilon D_t^\epsilon(u)| \leq 2\epsilon,$$

which concludes the proof of equivalence.

Using downcrossings in lieu of the pathwise local time, with a lot of work one can in fact obtain versions of Theorem 6.1 where the pointwise convergence in u is replaced by the uniform convergence, see Lemieux [16]. For the case of Brownian Motion (and thus any continuous local martingale) one can also consult Perkins [19], Chacon et al. [7] and Perkowsky and Prömel [20]. Our approach yields a weaker type of convergence, but it has a very simple proof, it works also for partitions not of Lebesgue-type, and it applies to any continuous semimartingale (if f is C^1). We recall the following fact, for which we refer to [22, Chapter 6, Theorem 1.7]:

$$(6.7) \quad 2 \int_0^\cdot \mathbf{1}_{\{X_s=u\}} dX_s = 2 \int_0^\cdot \mathbf{1}_{\{X_s=u\}} dV_s = \ell_\cdot(u) - \ell_\cdot(u-).$$

Proof of Theorem 6.2. Consider the convex function $f(x) := |x - u|$ and let $\text{sign}(x - u)$ be its left-derivative and $2\delta_u$ its second (distributional) derivative. Subtracting from the discrete-time Tanaka-Meyer formula (3.2) its continuous-time stochastic counterpart we get that

$$(6.8) \quad 0 = \int_0^t (H_s^{\pi_n}(u) - H_s(u)) dX_s + (L_t^{\pi_n, X}(u) - \ell_t(u))/2,$$

where using $\pi_n = (\tau_i^n)_i$ we define the predictable processes

$$H_s^{\pi_n}(u) := \sum_i \text{sign}(X_{\tau_i^n} - u) \mathbf{1}_{(\tau_i^n, \tau_{i+1}^n]}(s) \quad \text{and} \quad H_s(u) := \text{sign}(X_s - u).$$

Now $h^{\pi_n}(u) \rightarrow 0$ follows from (2.10) and (6.8) if we show that $\int_0^\cdot H_s^{\pi_n}(u) dX_s \rightarrow \int_0^\cdot H_s(u) dX_s$ in $\mathcal{S}^p$. To this end notice that

$$(6.9) \quad |H_s^{\pi_n}(u) - H_s(u)| \leq K_s^{\pi_n}(u) := 2 \times \mathbf{1}_{\{O_s(X, \pi_n) \geq |X_s - u|\}},$$

and that since X and $O(X, \pi_n)$ are continuous adapted processes, $K_s^{\pi_n}(u)$ is predictable, so it is enough to prove that $\int_0^\cdot K_s^{\pi_n}(u) dX_s \rightarrow 0$ in $\mathcal{S}^p$. Since $O_T^{\pi_n} \rightarrow 0$ a.s. implies that $K_t^{\pi_n}(u) \rightarrow 0$ a.s. on $\{X_t \neq u\}$ for all $t \leq T$, and since $K^{\pi_n} \leq 2$, the thesis follows from the (deterministic) dominated convergence theorem if $\|\int_0^\cdot \mathbf{1}_{\{X_s=u\}} dX_s\|_{\mathcal{S}^p} = 0$, which by (6.7) holds for all u if ℓ is continuous. Since Minkowski inequality for integrals says that

$$\left\| \int_0^T \mathbf{1}_{\{X_s=u\}} d|V|_s \right\|_{L^p(\mu)} \leq \int_0^T \|\mathbf{1}_{\{X_s=u\}}\|_{L^p(\mu)} d|V|_s = \int_0^T (\mu(\{X_s\}))^{1/p} d|V|_s,$$

if μ has no atoms (6.7) shows that $\|\int_0^\cdot \mathbf{1}_{\{X_s=u\}} dX_s\|_{\mathcal{S}^p} = 0$ for μ a.e. u , and so $h^{\pi_n} \rightarrow 0$ μ a.e.. Finally (2.10), (6.8) and (6.9) imply that

$$h^{\pi_n}(u) \leq C_p \left\| \int_0^\cdot 2(H_s^{\pi_n}(u) - H_s(u)) dX_s \right\|_{\mathcal{S}^p} \leq 4C_p \|X\|_{\mathcal{S}^p} \quad \text{for all } u \in \mathbb{R},$$

concluding the proof. $\square$

Proof of Theorem 6.1. Let $(\tau_m)_m$ a sequence of stopping times which prelocalizes X to $\mathcal{S}^p$ (see Emery [9, Theoreme 2]), i.e. $\tau_m \uparrow \infty$ a.s. and $X^{\tau_m-} \in \mathcal{S}^p$ for all m . Let $\mu_i(A) := |f''|(A \cap [-i, i])$ and set

$$G_n(\omega, T, u) := \sup_{t \leq T} |L_t^{X(\omega), \pi_n(\omega)}(u) - \ell_t(u, \omega)|$$

and $G_n^m := \mathbf{1}_{\{T < \tau_m\}} G_n$; then Theorem 6.2 implies that, as $n \rightarrow \infty$, G_n^m converges to 0 in $L^p(\mathbb{P} \times \mu_i)$, for all $m, i \in \mathbb{N}$ and $T \geq 0$. Passing to a subsequence (always without

relabelling) we can get convergence fast in $L^p(\mathbb{P} \times \mu_i)$ and so, for ω outside a $\mathbb{P}$ -null set $N_{i,m}^{p,T}$, $G_n^m(\omega, T, \cdot)$ converges to 0 in $L^p(\mu_i)$. Then along a diagonal subsequence we obtain that $G_n^m(\omega, T, \cdot)$ converges to 0 in $L^p(\mu_i)$ for all $i, m, p, T \in \mathbb{N} \setminus \{0\}$ for every ω outside the null set $N_{f''} := \cup_{i,m,T,p \in \mathbb{N} \setminus \{0\}} N_{i,m}^{p,T}$. Since $G_n = G_n^m$ on $\{T < \tau_m\}$, $G_n \rightarrow 0$ in $L^p(\mu_i)$ for all $i, p, T \in \mathbb{N} \setminus \{0\}$ for every ω outside $N_{f''}$. Since outside a compact set $G_n(\omega, T, \cdot) = 0$ for all n , convergence in $L^p(\mu_i)$ for arbitrarily big i, p implies convergence in $L^p(|f''|)$ for all $p \in [1, \infty)$. Since $G_n(\omega, \cdot, u) = 0$ is increasing, convergence for arbitrarily big T implies convergence for all $T \in (0, \infty)$. $\square$

7. DEPENDENCE ON THE PARTITIONS

In this section we investigate the extent to which the pathwise quadratic variation $\langle x \rangle^\Pi := \lim_n \langle x \rangle^{\pi_n}$ depends on the sequence of partitions $\Pi := (\pi_n)_n$. Instead of constructing explicit examples, we describe what happens for the general path of a Brownian motion and show that its pathwise quadratic variation depends in the most extreme way possible from $(\pi_n)_n$. Our work builds on two facts already mentioned (without proof) by Lévy in [18, Pag. 190]: that $\inf_\pi \langle x \rangle_1^\pi = 0$ for *every* continuous function x , and that for a.e. path $B(\omega)$ of a Brownian motion $\sup_\pi \langle B(\omega) \rangle_1^\pi = \infty$. The corresponding proofs can be found in Freedman [12, Pag. 47 and 48]; the second fact can be found in a strengthened form and with an alternative proof in Taylor [26, Corollary in Section 4].

To state the following theorem we need a couple of definitions. If $\pi = (\tau_n)_n$ is a random partition we denote by $\pi(\omega)$ the sequence $(\tau_n(\omega))_{n \in \mathbb{N}}$. Given sets C, D which depend on ω , we write that $C \subseteq D$ if $C(\omega) \subseteq D(\omega)$ holds for a.e. ω , and say that a sequence of random partition $(\pi_n)_{n \in \mathbb{N}}$ is *refining* if $\pi_n \subseteq \pi_{n+1}$ for all n . We denote by $\mathbb{N}/2^n$ the set $\{i/2^n : i \in \mathbb{N}\}$ of dyadics of order n . To be able to deal with a positive but potentially non-finite process A , we identify $[0, 1]$ (with the Euclidian topology) with $[0, \infty]$ using the bijection $1 - \exp(-x)$ (where $e^{-\infty} := 0$), and thus we endow $[0, \infty]$ with the distance $d(a, b) := |e^{-a} - e^{-b}|$, which makes it homeomorphic to $[0, 1]$ and for all $M < \infty$ satisfies $d(a, b) \leq |a - b| \leq Cd(a, b)$ for all $a, b \in [0, M]$ and some $C = C(M)$.

Theorem 7.1. *If B is a Brownian motion and A a jointly-measurable¹⁶ increasing process with values in $[0, \infty]$ and such that $A_0 = 0$, there exist refining random partitions π_n of $[0, \infty)$ such that $\mathbb{N}/2^n \subseteq \pi_n$ and for all ω outside a null set*

$$(7.1) \quad \langle B(\omega) \rangle_t^{\pi_n(\omega)} \rightarrow A_t(\omega) \quad \text{for all } t \in [0, \infty) \text{ as } n \rightarrow \infty;$$

if $0 \leq a < b < \infty$ the convergence in (7.1) is uniform on $t \in [a, b]$ for the ω 's at which $(A_t(\omega))_{t \in [a, b]}$ is continuous. Moreover, given arbitrary random partitions $(\bar{\pi}_n)_n$ one can choose $\pi_n = (\tau_n^i)_i$ such that $\bar{\pi}_n \subseteq \pi_n$ for all n and, if A is adapted, $\tau_n^i + 2^{-n}$ is a stopping time for each i, n .

It is insightful to contrast this result with the well known fact that, if $(\pi_n)_n$ is a sequence of *optional* partitions such that $\|\pi_n\| \rightarrow 0$ a.e., $\langle B(\omega) \rangle_t^{\pi_n(\omega)}$ converges to t uniformly on compacts in probability (see the first item of proposition 2.3). The random times $(\tau_n^i)_i$ making up π_n do not need to look far into the future to break

¹⁶Of course any *càdlàg* increasing process A is jointly-measurable. However this is not true for general increasing processes: for example if $A := Y1_{\{\tau\}} + 1_{(\tau, \infty)}$ where τ is an exponentially distributed random time and Y is a non-measurable function with values in $(0, 1)$ then A is a process with respect to the completed sigma-algebra (A_t is measurable since $A_t = 0$ a.e.), yet A is clearly not jointly-measurable.

the convergence of $\langle B(\omega) \rangle_t^{\pi_n(\omega)}$ to t : as the theorem states, one could take the $(\tau_n^i)_i$ to look only an arbitrarily small amount of time into the future.

We remark that in Theorem 7.1 no right-continuity assumptions are made on A , and that if $A(\omega)$ is finite valued then the convergence under the Euclidian distance $|a - b|$ is equivalent to the convergence under the distance $d(a, b)$. Also, notice that the random times making up π_n are bounded (since $(\tau_n^i)_i = \pi_n \supseteq \mathbb{N}/2^n$ implies $\tau_n^i \leq i/2^n$).

Although we stated Theorem 7.1 only for Brownian motion, it holds for any continuous stochastic process with an oscillatory behavior wild enough to have infinite 2-variation on any interval in the sense which is specified by Lemma A.2, i.e. such that for every $0 \leq c < d < \infty$ there exist random partitions π_n of $[c, d]$ along which the quadratic variation of B converges to infinity. In particular our proof of Lemma A.2 shows that Theorem 7.1 applies whenever B is a continuous adapted¹⁷ process for which there exists some continuous strictly increasing function ψ such that $\psi(h)/h^2 \rightarrow 0$ as $h \downarrow 0$ and

$$(7.2) \quad \text{for every } t \geq 0 \quad \limsup_{h \downarrow 0} \frac{\psi(|B_{t+h} - B_t|)}{h} \geq 1 \quad \text{a.s. .}$$

Once obtained Lemma A.2 using the section theorem, the proof of Theorem 7.1 is laborious but entirely elementary, as it rests entirely on Borel Cantelli's lemma and on the fact that, given a càdlàg adapted process D , its jumps of size bigger than a given constant are stopping times (for an elementary proof see [23, Theorem 3.1]).

We now explain the idea behind the proof, avoiding all the considerable amount of technicalities which arise from the dependence in ω (i.e. mostly tracking the null sets and ensuring measurability); the actual proof is presented in the appendix. So, fix ω and write $a(t) = A_t(\omega)$, $x(t) = B_t(\omega)$; the only properties which we will assume of the function x is that it is continuous and for every $0 \leq c < d < \infty$ there exist partitions π_n of $[c, d]$ such that the quadratic variation of x along π_n converges to infinity. We will now show that there exists a refining π_n which contains $\mathbb{N}/2^n \cup \bar{\pi}_n$ and such that $\langle x \rangle_t^{\pi_n} \rightarrow a(t)$ for all t .

W.l.o.g we can work on the time horizon $[0, 1]$. We will consider a bounded by 1, since the general case following simply using the distance d instead of the Euclidian distance. Note that, as observed already by Freedman [12], given $k \in \mathbb{N} \setminus \{0\}$ and π we can build a partition $\pi' \supseteq \pi$ such that $\langle x \rangle_t^{\pi'} = \langle x \rangle_t^\pi / k$; indeed it is enough to do so on each subinterval of π , so we can assume that $\pi = \{c, d\}$. If $x(c) = x(d)$ take $\pi' := \{c, d\}$; if $x(c) \neq x(d)$ we define $\pi' = (t_i)_{i=0}^k$ setting $t_0 := c$ and

$$t_i := \min\{t \in [c, d] : x(t) = x(c) + (x(d) - x(c))/k\} \quad \text{for } i = 1, \dots, k;$$

indeed $\langle x \rangle_t^{\pi'} = \sum_{i=0}^{k-1} ((x(d) - x(c))/k)^2 = \langle x \rangle_t^\pi / k$ holds. We will denote by $F(\pi, k)$ the partition π' built with the above construction starting from π and k .

We now prove the existence of some π' such that $|\langle x \rangle_t^{\pi'} - a(t)| \leq 1/2^n$; to do so we take $i \in \mathbb{N}$ such that $a(t) \in [i/2^n, (i+1)/2^n]$ and show that there exists π such that $\langle x \rangle_t^\pi \in [i, i+1]$ and then take $\pi' = F(\pi, 2^n)$; note that we automatically know such π exists when $i = 0$ (by taking $\pi = F(\tilde{\pi}, k)$ where $\tilde{\pi}$ is an arbitrary partition k a big enough integer). If $i \geq 1$ since the quadratic variation over $[0, t]$ equals¹⁸ the sum of the quadratic variations over the subintervals $[mt/i, (m+1)t/i]$, $m = 0, \dots, i-1$, by time translation it is enough to prove that for any $s > 0$ there exist $\tilde{\pi}'$ such that

¹⁷This is only used to obtain that $\tau_n^i + 2^{-n}$ are stopping times; otherwise B measurable is enough.

¹⁸This requires that π contains each endpoint of the subintervals; this does no harm, as it only means the π we have to build must contain these points.

$\langle x \rangle_s^{\tilde{\pi}'} \subseteq [1, 1 + 1/i]$. As we assumed above, there exist a partition $\tilde{\pi}$ such that $\langle x \rangle_s^{\tilde{\pi}}$ is arbitrarily large. Now using Freedman's construction with k equal to be the integer part of $\langle x \rangle_s^{\tilde{\pi}}$ we obtain $\tilde{\pi}' = F(\tilde{\pi}, k)$ such that $\langle x \rangle_s^{\tilde{\pi}'} \in [1, 1 + 1/k] \subseteq [1, 1 + 1/i]$, concluding our proof of the existence of some π' such that $|\langle x \rangle_t^{\pi'} - a(t)| \leq 1/2^n$.

Now, given any $\tilde{\pi}_n$, by applying the above reasoning to the increments of a on each subinterval of $\tilde{\pi}_n$, we can find a $\pi_n \supseteq \tilde{\pi}_n$ such that $|\langle x \rangle_t^{\pi_n} - a(t)| \leq 1/2^n$ simultaneously for all $t \in \tilde{\pi}_n$. If we define $(\tilde{\pi}_n, \pi_n)$ by induction setting $\tilde{\pi}_0 := \{0, 1\} =: \pi_0$ and taking $\tilde{\pi}_n$ to be the union of $\mathbb{N}/2^n \cup \tilde{\pi}_n$ with the times when a has a jump of size bigger than $1/n$ and with $\cup_{k < n} \pi_k$, and then building π_n from $\tilde{\pi}_n$ as explained at the beginning of this paragraph, we obtain a refining π_n which contains $\mathbb{N}/2^n \cup \tilde{\pi}_n$ and such that $\langle x \rangle_t^{\pi_n} \rightarrow a(t)$ simultaneously for all¹⁹ t , concluding our 'mock-up proof'.

APPENDIX A. PROOF OF THEOREM 7.1

In order to deal with the technicalities involved in tracking the dependence in ω , we need to introduce a number of new definitions; these boil down to asking that, when evaluated at each ω , random partitions are (deterministic) partitions and the operations defined on them correspond to the analogous operations for (deterministic) partitions. Given two random times $\sigma \leq \tau$, with slight abuse of notation we denote by $[\sigma, \tau]$ the set $\{(\omega, t) \in \Omega \times [0, \infty) : \sigma(\omega) \leq t \leq \tau(\omega)\}$. Given random times $\sigma \leq \tau$ we will say that $\pi = (\tau_k)_{k \in \mathbb{N}}$ is a *random partition of $[\sigma, \tau]$* if τ_k are random times such that $\tau_0 = \sigma, \tau_k \leq \tau_{k+1} \leq \tau$ with $\tau_k < \tau_{k+1}$ on $\{\tau_{k+1} < \tau\}$, and for a.e. ω there exists some $k = k(\omega)$ such that $\tau_{k(\omega)}(\omega) = \tau(\omega)$; we then denote by $K(\pi)$ the (*finite*) random variable

$$(A.1) \quad K(\pi) := \min\{k \in \mathbb{N} : \tau_k = \tau\} \text{ if } \pi = (\tau_k)_{k \in \mathbb{N}}.$$

We denote by $\mathcal{P}[\sigma, \tau]$ the set of random partitions of $[\sigma, \tau]$, with $\{\sigma\}$ the constant partition (i.e. $\{\sigma\} = (\sigma_i)_i$ with $\sigma_i = \sigma$ for all $i \in \mathbb{N}$), and with $\mathcal{P}[0, \infty)$ the set of random partitions of $[0, \infty)$ defined shortly before Definition 2.1 (one could more generally define the random partitions of $[\sigma, \tau]$; notice that for $(\tau_n)_n$ to be in $\mathcal{P}[\sigma, \tau]$ it is not required that $\tau_n = \tau$ for big enough n , unlike $\mathcal{P}[\sigma, \tau]$, so the set $\cup_n \{\tau_n(\omega)\}$ does not need to be finite). We now introduce several operations that one can perform on random partitions. Given random times $\alpha \leq \sigma \leq \tau \leq \beta$ and $(\tau_k)_k = \pi \in \mathcal{P}[\alpha, \beta]$ we define $\pi \cap [\sigma, \tau]$ to be the random partition $((\tau_k \wedge \tau) \vee \sigma)_k$ of $[\sigma, \tau]$; notice that $(\pi \cap [\sigma, \tau])(\omega)$ equals $(\pi(\omega) \cap [\sigma(\omega), \tau(\omega)]) \cup \{\sigma(\omega), \tau(\omega)\}$. Given a measurable partition $(A_n)_{n \in \mathbb{N}}$ of Ω and for each n a random quantity τ_n defined on A_n , one can define on Ω a random quantity τ by setting $\tau := \tau_n$ on A_n ; we will sometimes use this construction to define random times (and thus random partitions). Given random partitions $\pi = (\tau_n)_n$ of $[\sigma, \tau]$ and $\tilde{\pi} = (\tilde{\tau}_n)_n$ of $[\tilde{\sigma}, \tilde{\tau}]$, we define by induction the random partition $\pi \cup \tilde{\pi} = (\rho_n)_n$ of $[\sigma \wedge \tilde{\sigma}, \tau \vee \tilde{\tau}]$ as follows: $\rho_0 := \sigma \wedge \tilde{\sigma}$, if $\rho_n(\omega) = \tau(\omega) \vee \tilde{\tau}(\omega)$ then $\rho_{n+1}(\omega) := \tau(\omega) \vee \tilde{\tau}(\omega)$, and if $\rho_n(\omega) < \tau(\omega) \vee \tilde{\tau}(\omega)$ then

$$\rho_{n+1}(\omega) := \min\{t > \rho_n(\omega) : t \in \pi(\omega) \cup \tilde{\pi}(\omega) \cup \{\tau(\omega) \vee \tilde{\tau}(\omega)\}\};$$

notice that the ρ_n are indeed random times, as it follows from the following representation, where given a random time τ and a measurable set A we denote by τ^A the random time $\tau^A := \tau$ on A and $\tau^A := \infty$ on $\Omega \setminus A$:

$$\rho_{n+1} = \min_k (\tau_k^{\{\tau_k > \rho_n\}} \wedge \tilde{\tau}_k^{\{\tilde{\tau}_k > \rho_n\}} \wedge (\tau \vee \tilde{\tau})).$$

¹⁹The convergence holds for any dyadic time and any time of jump of a , and thus it holds for all t as explained in Lemma A.6.

Given $\pi^i \in \mathcal{P}[\sigma_i, \tau_i]$ for $i \leq k$ we can analogously define $\cup_{i=0}^k \pi^i \in \mathcal{P}[\min_i \sigma_i, \max_i \tau_i]$; in particular when $\pi^i = \{\sigma_i\}$ for each i this defines $\cup_{i=0}^k \{\sigma_i\} = (\rho_n)_{n \in \mathbb{N}}$ as an element of $\mathcal{P}[\min_i \sigma_i, \max_i \sigma_i]$ (the point being that the $(\rho_n)_n$ are ordered whereas the $(\sigma_i)_i$ in general are not). Notice that we cannot reasonably define the random partition $\cup_{i \in \mathbb{N}} \pi^i$ for general $(\pi^i)_{i \in \mathbb{N}}$; indeed in general the set $\cup_{i \in \mathbb{N}} \pi^i(\omega)$ is not finite, so there is no random partition π' such that $\pi'(\omega) = \cup_{i \in \mathbb{N}} \pi^i(\omega)$ for a.e. ω . However, if $\pi = (\tau_i)_i \in \mathcal{P}[\sigma, \tau]$ and $\pi^i \in \mathcal{P}[\tau_i, \tau_{i+1}]$ for each $i \in \mathbb{N}$, we can define $\cup_{i \in \mathbb{N}} \pi^i = (\rho_n)_n \in \mathcal{P}[\sigma, \tau]$ by induction like above: $\rho_0 := \sigma$, if $\rho_n(\omega) = \tau(\omega)$ then $\rho_{n+1}(\omega) := \tau(\omega)$, and if $\rho_n(\omega) < \tau(\omega)$ then

$$(A.2) \quad \rho_{n+1}(\omega) := \min\{t > \rho_n(\omega) : t \in \cup_{i \in \mathbb{N}} \pi^i(\omega) \cup \{\tau(\omega)\}\};$$

since for fixed ω the set $\pi(\omega)$ is finite, also $\cup_{i \in \mathbb{N}} \pi^i(\omega)$ is finite; thus the minimum in (A.2) exists, and $\sigma_K = \tau$ for some $K = K(\omega)$, so $\cup_{i \in \mathbb{N}} \pi_i \in \mathcal{P}[\sigma, \tau]$. Analogously if $\pi = (\tau_i)_i \in \mathcal{P}[0, \infty)$ and $\pi^i \in \mathcal{P}[\tau_i, \tau_{i+1}]$ we can define $\cup_{i \in \mathbb{N}} \pi^i = (\rho_n)_n \in \mathcal{P}[0, \infty)$ such that $\rho_n \leq \tau_n$ for all n by setting $\rho_0 := 0$ and

$$\rho_{n+1}(\omega) := \min\{t > \rho_n(\omega) : t \in \cup_{i \in \mathbb{N}} \pi^i(\omega)\},$$

where the minimum exists and $\rho_n \uparrow \infty$ since $\cup_{i \in \mathbb{N}} \pi^i(\omega)$ is finite on compacts.

Recall the definitions given in (2.5)–(2.8). Note that given finite random times $\alpha \leq \sigma \leq \tau \leq \beta$ and $\pi \in \mathcal{P}[\alpha, \beta]$ the random variable $\langle B \rangle_{(\sigma, \tau]}^\pi$ is defined by (2.5) path by path, i.e., $\langle B \rangle_{(\sigma, \tau]}^\pi(\omega) := \langle B(\omega) \rangle_{(\sigma(\omega), \tau(\omega))}^{\pi(\omega)}$. Thanks to the next simple lemma, in the rest of this section we only need to consider $[0, 1]$ -valued random times; in particular $\pi(\omega)$ will be a finite set for a.e. ω for any random partition π and $\langle B \rangle_{(\sigma, \tau]}^\pi$ will always be well defined.

Scholium A.1. *It is enough to prove Theorem 7.1 on $\{t \in [0, 1]\}$.*

Proof. For $k \in \mathbb{N}$ applying Theorem 7.1 on the time interval $[0, 1]$ to the Brownian motion $B_t^k := B_{t+k} - B_k$, the increasing process $A_t^k := A_{t+k} - A_k$ and $\bar{\pi}_n^k := (\bar{\pi}_n \cap [k, k+1]) - k$ produces a refining sequence $(\pi_n^k)_n \subseteq \mathcal{P}[0, 1]$ such that $\pi_n^k \supseteq \bar{\pi}_n^k$ for all n and $\langle B \rangle_t^{\pi_n^k}$ converges a.s. to A_t uniformly on $t \in [0, 1]$. Since $(k)_{k \in \mathbb{N}}$ is a ‘random’ partition of $[0, \infty)$ and $\pi_n^k + k \in \mathcal{P}[k, k+1]$, we can define $\pi_n := \cup_{k \in \mathbb{N}} \pi_n^k + k$, which is a random partition of $[0, \infty)$ that trivially gives Theorem 7.1 on the time interval $[0, \infty)$. $\square$

Lévy stated that for a.e. ω there exist partitions $\pi_n = \pi_n(\omega)$ s.t. $\lim_n \langle B(\omega) \rangle_{(0, 1]}^{\pi_n} = \infty$. We now need to strengthen this result showing that one can choose these partitions *in a measurable way*. To do so, we need to revisit the proof of [26, Theorem 1 and its Corollary in Section 4] and delve into the proof of the existence of a Vitali subcover to show how one can choose a measurable one (on a set of probability arbitrarily close to 1); this will follow from an application of the section theorem.

In the proof of the next lemma we will use the following notation: given a subset E of $(0, 1) \times \Omega$ and $\omega \in \Omega$, we set $E(\omega) := \{t : (t, \omega) \in E\}$, $E(t) := \{\omega : (t, \omega) \in E\}$ and $\Pi_\Omega(E) := \{\omega : (t, \omega) \in E \text{ for some } t \in (0, 1)\}$. With $\mathcal{B}_1 \times \mathcal{F}$ we will denote the product sigma algebra of the Borel sets $\mathcal{B}_1$ of $(0, 1)$ with the underlying sigma algebra $\mathcal{F}$ on Ω ; whenever a function of (t, ω) (or a subsets of $(0, 1) \times \Omega$) is $\mathcal{B}_1 \times \mathcal{F}$ -measurable, we will simply say that is measurable. We will assume that $\mathcal{F}$ contains all null sets; this is without loss of generality because of [13, Chapter 1, Lemma 1.19]. The Lebesgue measure on $(0, 1)$ will be denoted with $\mathcal{L}^1$, and the dyadics (resp. the dyadics of order n) in $(0, 1)$ with D (resp. D_n), i.e. $D_n := [0, 1] \cap \mathbb{N}2^{-n}$ and $D = \cup_{n \geq 0} D_n$. As usual the inf (resp. sup) of the empty set is defined to be ∞ (resp. $-\infty$).

Lemma A.2. *For every $0 \leq a < b$ there exist $\pi^n \in \mathcal{P}[a, b]$ such that*

$$\langle B \rangle_{(a,b)}^{\pi^n} \rightarrow \infty \text{ a.s. as } n \rightarrow \infty.$$

Proof. Step 1. Brownian motion satisfies (7.2) with $\psi(h) := h^2/(2 \log \log(1/h))$ since $\phi(h) := \sqrt{2h \log \log(1/h)}$ is asymptotically inverse to ψ (meaning that $\phi(\psi(h))/h \rightarrow 1$ and $\psi(\phi(h))/h \rightarrow 1$ as $h \downarrow 0$) and by the iterated log law

$$\limsup_{h \downarrow 0} \frac{|B_{t+h} - B_t|}{\phi(h)} = 1 \text{ a.s. .}$$

Moreover also the process $X_t := (B_{t(b-a)+a} - B_a)/\sqrt{b-a}$ satisfies (7.2) (with the same ψ), so we can without loss of generality take $a = 0, b = 1$. For $k, n \in \mathbb{N}$, $t, \epsilon \in (0, 1)$ and $h \in F \subset (0, 1]$ define $Y_t^h := \psi(|B_{t+h} - B_t|)/h$,

$$(A.3) \quad E(F) := \{(t, \omega) \in (0, 1) \times \Omega : Y_t^h > 1 - \epsilon \text{ for some } h \in F\},$$

$E_k^n := E((0, 1/2^k] \cap D_n)$ and $E_k := E((0, 1/2^k])$. Since Y_t^h and $Y_t(n) := \max\{Y_t^h : h \in (0, 1/2^k] \cap D_n\}$ are continuous in t and measurable in ω , Y^h and $Y(n)$ are measurable. It follows that $E_k^n = \{Y(n) > 1 - \epsilon\}$ is measurable, and so also is $\cup_n E_k^n = E((0, 1/2^k] \cap D)$. Since Y_t^h is continuous in h , E_k equals $E((0, 1/2^k] \cap D)$ and thus it is measurable, and in particular $E := \cap_k E_k$ is measurable. Notice that (7.2) shows that $\mathbb{P}(E_k(t)) = 1$ for each t, k , and so $\mathbb{P}(E(t)) = 1$ for each t . Fubini's theorem applied to the product of $\mathbb{P}$ with $\mathcal{L}^1$ shows that $\mathcal{L}^1(E_k(\omega)) = 1 = \mathcal{L}^1(E(\omega))$ for $\mathbb{P}$ a.e. ω , and in particular $\Pi_\Omega(E) = \{\omega : E(\omega) \neq \emptyset\}$ has probability 1. Define for every $\omega \in \Pi_\Omega(E)$ and $n \in \mathbb{N}$

$$\mathcal{J}^n(\omega) := \{[t, t+h] : h \in (0, 1/2^n], h+t < 1, (t, \omega) \in E \text{ and } Y_t^h(\omega) > 1 - \epsilon\};$$

since by definition E is the set of (t, ω) for which there exist arbitrarily small $h > 0$ such that $Y_t^h > 1 - \epsilon$, $\mathcal{J}^n(\omega)$ is a Vitali cover of $E(\omega)$ for every $\omega \in \Pi_\Omega(E)$. It follows from Vitali's covering theorem [17, Theorem 1.31] that for every $\omega \in \Pi_\Omega(E)$ there exist $N^n(\omega) < \infty$ and $(\{t_i^n, h_i^n\}(\omega))_{i=1}^{N^n(\omega)}$ such that for all $i \neq j$ and $\omega \in \Omega$

$$(A.4) \quad \mathcal{J}^n(\omega) \supseteq [t_i^n, t_i^n + h_i^n](\omega) =: I_i^n(\omega), I_i^n(\omega) \cap I_j^n(\omega) = \emptyset, \sum_{i=1}^{N^n} h_i^n(\omega) > 1 - \epsilon.$$

Assume for the moment that t_i^n, h_i^n, N^n depended measurably in ω . Since on $\Pi_\Omega(E)$

$$Y^n := \sum_i \psi(|B_{t_i^n + h_i^n} - B_{t_i^n}|) \geq \sum_i h_i^n(1 - \epsilon) \geq (1 - \epsilon)^2 > 0$$

and any interval in $\mathcal{J}^n(\omega)$ has length at most $1/2^n$, $\lim_{s \downarrow 0} \psi(s)/s^2 = 0$ implies that

$$\sum_i (B_{t_i^n + h_i^n} - B_{t_i^n})^2 \rightarrow \infty \quad \text{on } \Pi_\Omega(E) \text{ and so a.s.,}$$

and so if $\pi^n = (s_k)_k$ is the random partition made of $0, 1$ and the points t_i^n and $t_i^n + h_i^n$ for $i = 1, \dots, N^n$ we get that $\langle B \rangle_{(0,1)}^{\pi^n} \rightarrow \infty$ a.s..

Step 2. Thus, to conclude the proof it is enough to show that one can choose t_i^n, h_i^n, N^n which depend measurably in ω and satisfy (A.4) for all ω . While we cannot quite do that, by revisiting the proof of Vitali's covering theorem and applying the section theorem (for an elementary proof of which we refer to [1, 2, Theorem 3.1]) and its immediate corollary [22, Chapter 1, Theorem 4.14] we obtain measurable t_i^n, h_i^n, N^n which satisfy (A.4) for all $\omega \in V_n$, where V_n is a large set, and this allows us to conclude the proof as we explain after (A.6). While on V_n necessarily $t_i^n, h_i^n \in (0, 1]$ for $i \leq N^n$, in general our t_i^n, h_i^n may also take the values 0 and ∞ . Indeed, in Steps 3,4 we will construct by induction on $i \geq 1$ random times t_i^n, h_i^n

which satisfy the properties stated below in (A.6) relative to the objects which we will now define. Set

$$V_n := \Pi_\Omega(E) \cap (\cap_{i \geq 1} \{\mathfrak{t}_i^n + \mathfrak{h}_i^n < \infty\})$$

and define the decreasing family of random intervals $(\mathcal{J}_i^n)_i$ setting $\mathcal{J}_1^n := \mathcal{J}^n \neq \emptyset$ on $\Pi_\Omega(E)$ and $\mathcal{J}_1^n := \emptyset$ otherwise and, given

$$(A.5) \quad C_i^n := \{\mathfrak{t}_i^n + \mathfrak{h}_i^n < \infty\} \cap \{\mathcal{J}_i^n \neq \emptyset\},$$

we define by induction

$$\mathcal{J}_{i+1}^n := \{[t, t+h] \in \mathcal{J}_i^n : [t, t+h] \cap [\mathfrak{t}_i^n, \mathfrak{t}_i^n + \mathfrak{h}_i^n] = \emptyset\} \text{ on } C_i^n, \quad \mathcal{J}_{i+1}^n := \emptyset \text{ otherwise,}$$

and then we set

$$S^i := \sup\{h \in (0, 1] : [t, t+h] \in \mathcal{J}_i^n, t \in (0, 1)\} \vee 0,$$

so that $\{S^i = 0\} = \{\mathcal{J}_i^n = \emptyset\}$. In Steps 3,4 we will construct $\mathfrak{t}_i^n, \mathfrak{h}_i^n$ such that

$$(A.6) \quad [\mathfrak{t}_i^n, \mathfrak{t}_i^n + \mathfrak{h}_i^n] \in \mathcal{J}_i^n \text{ and } 2\mathfrak{h}_i^n > S^i > 0 \text{ on } C_i^n$$

$$\mathfrak{h}_i^n = 0 \text{ on } \{\mathcal{J}_i^n = \emptyset\} = \{\mathfrak{t}_i^n = 0\}, \quad \mathbb{P}(V_n) \geq 1 - 1/2^n;$$

once obtained such random times $(\mathfrak{t}_i^n, \mathfrak{h}_i^n)_{i \geq 0}$, the proof proceeds as follows. From (A.6), the proof of Vitali's covering theorem (see [17, Theorem 1.31]) shows that $\mathcal{L}^1(E(\omega) \setminus \cup_{i \geq 1} [\mathfrak{t}_i^n, \mathfrak{t}_i^n + \mathfrak{h}_i^n](\omega)) = 0$ for $\omega \in V_n$, and so (since we proved that $\mathcal{L}^1(E(\omega)) = 1$) $N^n := \inf\{k : \sum_{i=1}^k \mathfrak{h}_i^n > 1 - \epsilon\}$ is a *finite* random variable on V_n . Notice that $\mathfrak{h}_i^n > 0$ for all $i \leq N^n$, since $\{\mathfrak{h}_i^n = 0\} = \{\mathcal{J}_i^n = \emptyset\}$ is increasing in i . Thus N^n and $(\mathfrak{t}_i^n, \mathfrak{h}_i^n)_{i=1}^{N^n}$ satisfy (A.4) on V_n for all $i \neq j$, and thus if $\pi^n = (s_k)_k$ is the random partition made of 0,1 and the points $\mathfrak{t}_i^n$ and $\mathfrak{t}_i^n + \mathfrak{h}_i^n$ for $i = 1, \dots, N^n$, reasoning as in Step 1 we have that $Y^n \geq (1 - \epsilon)^2$ on V_n . It follows that $\langle B \rangle_{(0,1]}^{\pi^n}(\omega) \rightarrow \infty$ if $\omega \in V_n$ for infinitely many n 's, and so by Borel Cantelli's lemma $\langle B \rangle_{(0,1]}^{\pi^n}(\omega) \rightarrow \infty$ a.s. since $\mathbb{P}(\Omega \setminus V_n) \leq 1/2^n$.

Step 3. To conclude the proof we need, for fixed n , to define random times $\mathfrak{t}_i^n, \mathfrak{h}_i^n$ which satisfy (A.6). We will so do in Step 4, using the auxiliary processes L^i which we introduce in this step. Given $\mathcal{J}_i^n$ (which so far we only defined for $i = 1$) and $F \subseteq (0, 1/2^n]$, define $L^i(F) : (0, 1) \times \Omega \rightarrow [0, 1]$ as

$$(A.7) \quad L_t^i(F)(\omega) := \sup\{h \in F : [t, t+h] \in \mathcal{J}_i^n(\omega)\} \vee 0,$$

and set $L^i := L^i((0, 1/2^n])$. We now need to prove that L^1 is measurable. Notice that, since Y_t^h is continuous in h , $L^1 = \sup_{k \geq n} L^1(D_k \cap (0, 1/2^n])$. As we proved E and Y_t^h are measurable, and so such is

$$A_h^1 := \{(t, \omega) \in E : t < 1 - h, Y_t^h > 1 - \epsilon\}.$$

Since $L^1(D_k \cap (0, 1/2^n]) = i/2^k$ on $A_{i/2^k}^1 \setminus (\cup_{j=i+1}^{2^k-n} A_{j/2^k}^1)$ for $i = 1, \dots, 2^{k-n}$ and $L^1(D_k \cap (0, 1/2^n]) = 0$ otherwise, $L^1(D_k \cap (0, 1/2^n])$ and thus L^1 are measurable.

In Step 4 we will build random times $\mathfrak{t}_1^n, \mathfrak{h}_1^n$ from L^1 . From $\mathfrak{t}_1^n, \mathfrak{h}_1^n$ one can define $\mathcal{J}_2^n$ as done after equation (A.5) and thus L^2 as specified in (A.7). One can then iterate the above procedure and define $\mathfrak{t}_i^n, \mathfrak{h}_i^n$ by induction on $i \geq 1$: from a measurable L^2 build random times $\mathfrak{t}_2^n, \mathfrak{h}_2^n$ as explained in Step 4, and from them build $\mathcal{J}_3^n$ and a measurable L^3 etc. For this to work we need to show that L^i built from $\mathcal{J}_i^n$ (and thus from $\mathcal{J}_1^n$ and the random times $(\mathfrak{t}_j^n, \mathfrak{h}_j^n)_{j=1}^{i-1}$) is measurable for all $i \geq 2$; we now do so for $i = 2$, the general case being only notationally more complicated. If $F \subseteq (0, 1/2^n]$, from the definition of $\mathcal{J}_2^n$ it follows that $L_t^2(F)$ equals

$$\bar{L}_t^2(F) := \sup\{h \in F : [t, t+h] \in \mathcal{J}^n \text{ and } [t, t+h] \cap [\mathfrak{t}_1^n, \mathfrak{t}_1^n + \mathfrak{h}_1^n] = \emptyset\} \vee 0$$

on C_1^n , whereas on $\Omega \setminus C_1^n$ we have $L_t^2(F) = 0$. Since $\mathfrak{t}_1^n, \mathfrak{h}_1^n$ are random times and $\{\mathcal{J}_1^n \neq \emptyset\}$ is $\mathcal{F}$ -measurable (as proved²⁰ in Step 4), C_1^n is $\mathcal{F}$ -measurable; thus, it is enough to prove that $\bar{L}_t^2(F)$ is measurable. The proof is basically the same as for L^1 : since A_h^1 is measurable, such is $A_h^2 := A_h^1 \cap B_h^1$ where

$$B_h^1 := \{(t, \omega) \in E : t > \mathfrak{t}_1^n + \mathfrak{h}_1^n\} \cup \{(t, \omega) \in E : t + h < \mathfrak{t}_1^n\},$$

and since $\bar{L}^2(D_k \cap (0, 1/2^n]) = i/2^k$ on $A_{i/2^k}^2 \setminus (\cup_{j=i+1}^{2^{k-n}} A_{j/2^k}^2)$ for $i = 1, \dots, 2^{k-n}$ and $\bar{L}^2(D_k \cap (0, 1/2^n]) = 0$ otherwise, $\bar{L}^2(D_k \cap (0, 1/2^n])$ is measurable and thus so is $\bar{L}^2 = \sup_{k \geq n} \bar{L}^2(D_k \cap (0, 1/2^n])$.

Step 4. In this step we explain how to use a measurable L^i to build random times $\mathfrak{t}_i^n, \mathfrak{h}_i^n$ which satisfy the first 3 statements of (A.6) and

$$(A.8) \quad \mathbb{P}(\mathfrak{t}_i^n + \mathfrak{h}_i^n = \infty) \leq 1/2^{n+i};$$

since $\mathbb{P}(\Pi_\Omega(E)) = 1$, it follows from (A.8) that $\mathbb{P}(V_n) \geq 1 - 1/2^n$, so $(\mathfrak{t}_i^n, \mathfrak{h}_i^n)_{i \geq 1}$ satisfy (A.6), concluding the proof. Notice that, despite the fact that $(0, 1)$ is uncountable, $S^i = \sup_{t \in (0, 1)} L_t^i$ is also measurable with respect to the (complete) sigma algebra $\mathcal{F}$: this follows from²¹ [22, Chapter 1, Theorem 4.14] and the identity $\{S^i > \lambda\} = \Pi_\Omega(\{L^i > \lambda\})$, which holds for all $\lambda \in \mathbb{R}$. It follows that $\Pi_\Omega(\{L^i > S^i/2\}) = \{S^i > 0\} = \{\mathcal{J}_i^n \neq \emptyset\}$ is $\mathcal{F}$ -measurable, and since L^i is measurable we can apply the section theorem (with the constant filtration $\mathcal{F}_t := \mathcal{F}$) to $\{L^i > S^i/2\}$ and obtain a random time $\bar{\mathfrak{t}}_i^n$ such that $\mathbb{P}(\bar{\mathfrak{t}}_i^n = \infty \text{ and } \mathcal{J}_i^n \neq \emptyset) \leq 1/2^{n+i+1}$ and $L_{\bar{\mathfrak{t}}_i^n}^i > S^i/2$ (and in particular $\mathcal{J}_i^n \neq \emptyset$ and $\bar{\mathfrak{t}}_i^n > 0$) on $\{\bar{\mathfrak{t}}_i^n < \infty\}$. We then define $\mathfrak{t}_i^n$ to equal $\bar{\mathfrak{t}}_i^n$ on $\{\mathcal{J}_i^n \neq \emptyset\}$ and to equal 0 otherwise. In particular $\{\mathfrak{t}_i^n = \infty\} \cap \{\mathcal{J}_i^n \neq \emptyset\} = \{\bar{\mathfrak{t}}_i^n = \infty\}$ and so $\mathbb{P}(\mathfrak{t}_i^n = \infty) \leq 1/2^{n+i+1}$, on $\{\mathfrak{t}_i^n \in (0, \infty)\}$ we have $\mathfrak{t}_i^n = \bar{\mathfrak{t}}_i^n$, $L_{\mathfrak{t}_i^n}^i > S^i/2$ and $\{\mathcal{J}_i^n \neq \emptyset\}$, and finally $\{\mathfrak{t}_i^n = 0\} = \{\mathcal{J}_i^n = \emptyset\}$. Define

$$G_i := \{(h, \omega) \in (0, 1/2^n] \times \Omega : \mathfrak{t}_i^n \in (0, \infty), [\mathfrak{t}_i^n, \mathfrak{t}_i^n + h] \in \mathcal{J}_i^n, h > S^i/2\},$$

which is measurable since $S^i, \mathfrak{t}_i^n$ and $(\mathfrak{t}_j^n, \mathfrak{h}_j^n)_{j=1}^{i-1}$ are $\mathcal{F}$ -measurable and Y_t is measurable. Since $\{\mathfrak{t}_i^n \in (0, \infty)\} = \Pi_\Omega(G_i)$, by applying the section theorem to G_i we find a random time $\bar{\mathfrak{h}}_i^n$ such that $\mathbb{P}(\bar{\mathfrak{h}}_i^n = \infty \text{ and } \mathfrak{t}_i^n \in (0, \infty)) \leq 1/2^{n+i+1}$ and $(\bar{\mathfrak{h}}_i^n(\omega), \omega) \in G_i$ for $\omega \in \{\bar{\mathfrak{h}}_i^n < \infty\}$. We then define $\mathfrak{h}_i^n$ to equal 0 on $\{\mathfrak{t}_i^n = 0\}$ and to equal $\bar{\mathfrak{h}}_i^n$ otherwise. In particular $\{\mathfrak{h}_i^n = \infty\} \cap \{\mathfrak{t}_i^n < \infty\} = \{\bar{\mathfrak{h}}_i^n = \infty\} \cap \{\mathfrak{t}_i^n \in (0, \infty)\}$ has probability at most $1/2^{n+i+1}$, so (A.8) holds. Notice that $\{\mathfrak{h}_i^n = 0\} = \{\mathfrak{t}_i^n = 0\} = \{\mathcal{J}_i^n = \emptyset\}$, and on $\{\mathfrak{t}_i^n \in (0, \infty), \mathfrak{h}_i^n < \infty\} = C_i^n$ we have $\bar{\mathfrak{h}}_i^n = \mathfrak{h}_i^n < \infty$ and so $\mathfrak{h}_i^n > S^i/2 > 0$ and $[\mathfrak{t}_i^n, \mathfrak{t}_i^n + h] \in \mathcal{J}_i^n$; thus we have defined random times $\mathfrak{t}_i^n, \mathfrak{h}_i^n$ which satisfy (A.8) and the first 3 statements of (A.6), concluding the proof. $\square$

We now strengthen the previous result as to make the quadratic variation to be exploding in all (non-trivial) intervals simultaneously.

Lemma A.3. *There exist $\pi_n \in \mathcal{P}[0, 1]$ such that*

$$\lim_n \langle B \rangle_{(\sigma, \tau]}^{\pi_n} \rightarrow \infty \text{ a.s. on } \{\sigma < \tau\} \text{ as } n \rightarrow \infty \text{ for all random times } 0 \leq \sigma \leq \tau \leq 1.$$

Note that the previous equality is required to hold only on $\{\sigma < \tau\}$ since trivially $\langle B \rangle_{(\sigma, \tau]}^\pi = 0$ on $\{\sigma = \tau\}$.

²⁰In Step 4 we use the measurability of L^i to prove that $\{\mathcal{J}_i^n \neq \emptyset\} = \{S^i > 0\}$ is $\mathcal{F}$ -measurable.

²¹For a proof of this result one can consult [5, Theorem A.5.10].

Proof. Lemma A.2 gives for each $n \in \mathbb{N} \setminus \{0\}$ and $i = 0, 1, \dots, 2^{n-1}$ some $\pi_n^i \in \mathcal{P}[i/2^n, (i+1)/2^n]$ such that $\mathbb{P}(\langle B \rangle_{\pi_n^i} \leq 2^n) \leq 2^{-n}$. Define $\pi_n := \cup_{i=0}^{2^n-1} \pi_n^i \in \mathcal{P}[0, 1]$. Now given $\sigma \leq \tau$ take $\omega \in \{\tau - \sigma > 2/2^n\}$, so there exists $i = i(\omega)$ such that

$$[i/2^n, (i+1)/2^n](\omega) \subseteq [\sigma, \tau](\omega),$$

and hence, using (2.7), we see that

$$\langle B \rangle_{[i/2^n, (i+1)/2^n]}^{\pi_n}(\omega) \leq \langle B \rangle_{(\sigma, \tau]}^{\pi_n}(\omega)$$

and since $\pi_n \cap [i/2^n, (i+1)/2^n] = \pi_n^i \cap [i/2^n, (i+1)/2^n]$ we get that

$$\langle B \rangle_{[i/2^n, (i+1)/2^n]}^{\pi_n}(\omega) = \langle B \rangle_{[i/2^n, (i+1)/2^n]}^{\pi_n^i}(\omega) = \langle B \rangle_{\pi_n^i}(\omega),$$

Putting everything together we get that

$$\{\langle B \rangle_{(\sigma, \tau]}^{\pi_n} \leq 2^n \text{ and } \tau - \sigma > 2/2^n\} \subseteq \cup_{i=0}^{2^n-1} \{\langle B \rangle_{\pi_n^i}(\omega) \leq 2^n \text{ and } \tau - \sigma > 2/2^n\},$$

and so the Borel-Cantelli lemma gives the result. $\square$

The following lemma states in probabilistic terms the fact that quadratic variation along the partition π^d (resp. π^u) is only slightly bigger than 0 (resp. 1).

Lemma A.4. *Given random times $0 \leq \sigma \leq \tau \leq 1$, $\pi \in \mathcal{P}[\sigma, \tau]$ and a random variable Z with values in $\mathbb{N} \setminus \{0\}$, there exists $\pi' \in \mathcal{P}[\sigma, \tau]$ such that $\pi \subseteq \pi'$ and*

$$\langle B \rangle_{\pi'} = \langle B \rangle_{\pi} / Z.$$

In particular for any $\varepsilon > 0$ there exist $\pi^d, \pi^u \in \mathcal{P}[\sigma, \tau]$ such that $\pi^d \supseteq \pi \subseteq \pi^u$,

$$\mathbb{P}\left(\langle B \rangle_{\pi^d} > \frac{1}{Z}\right) < \varepsilon \quad \text{and} \quad \mathbb{P}\left(\langle B \rangle_{\pi^u} \notin \left[1, 1 + \frac{1}{Z}\right] \text{ and } \sigma < \tau\right) < \varepsilon.$$

Proof. By working separately on each subinterval $[\sigma_i, \sigma_{i+1}]$ of $\pi = (\sigma_i)_i$, to find π' we can assume w.l.o.g. that $\sigma_0 = \sigma, \sigma_{i+1} = \tau$ for all $i \in \mathbb{N}$. Define

$$\sigma'_i := \min\{t \geq \sigma : B_t = \frac{(B_\tau - B_\sigma)(i \wedge Z)}{Z} + B_\sigma\} \quad \text{on } \{B_\tau \neq B_\sigma\}$$

and $\sigma'_0 := \sigma, \sigma'_{i+1} := \tau$ on $\{B_\tau = B_\sigma\}$; then $\pi \subseteq \pi' := (\sigma'_i)_{i \in \mathbb{N}} \in \mathcal{P}[\sigma, \tau]$ and

$$\langle B \rangle_{\pi'} = \sum_i (B_{\sigma'_{i+1}} - B_{\sigma'_i})^2 = \left(\frac{B_\tau - B_\sigma}{Z}\right)^2 Z = \langle B \rangle_{\pi} / Z.$$

Now fix $\varepsilon > 0$, and apply the previous result to find some $\pi' = \pi'_n$ such that

$$\langle B \rangle_{\pi'_n} = \langle B \rangle_{\pi} / n \rightarrow 0;$$

taking $\pi^d := \pi'_n$ for n big enough shows that $\mathbb{P}(\langle B \rangle_{\pi^d} > \frac{1}{Z}) < \varepsilon$.

Finally let π_n be as in Lemma A.3 and let $\pi'_n \in \mathcal{P}[\sigma, \tau]$ be such that $\pi'_n \supseteq \pi_n$ and

$$\langle B \rangle_{\pi'_n} = \langle B \rangle_{\pi_n} / Y_n \quad \text{where} \quad Y_n := \max\{k \in \mathbb{N} : k \leq \langle B \rangle_{\pi_n}\} \vee 1.$$

Notice that $\langle B \rangle_{\pi'_n} \leq 1 + 1/Y_n$ and on $\langle B \rangle_{\pi_n} \geq 1$ we have that $\langle B \rangle_{\pi'_n} \geq 1$; moreover $Y_n \geq \langle B \rangle_{\pi_n} - 1 \rightarrow \infty$ a.s. on $\{\sigma < \tau\}$. Taking $\pi^u := \pi'_n$ for n big enough it follows that $\mathbb{P}(\langle B \rangle_{\pi^u} \notin [1, 1 + \frac{1}{Z}] \text{ and } \sigma < \tau) < \varepsilon$. $\square$

We now essentially prove the convergence at any fixed time.

Lemma A.5. *Given random times $0 \leq \sigma \leq \tau \leq 1$ and a random variable Y with values in $[0, \infty]$, there exist $\pi_n \in \mathcal{P}[\sigma, \tau]$ such that*

$$\langle B \rangle_{(\sigma, \tau]}^{\pi_n} \rightarrow Y \text{ a.s. on } \{\sigma < \tau\} \text{ as } n \rightarrow \infty.$$

Proof. On $\{\sigma = \tau\}$ we define $\pi_n = \{\sigma\}$ for all n , and on $\{Y = \infty, \sigma < \tau\}$ we set π_n equal to the random partition π_n given by lemma A.3; this clearly gives the thesis on $\{Y = \infty\} \cup \{\sigma = \tau\}$. To conclude we will define π_n separately on each $\{Y \in [i/2^n, (i+1)/2^n), \sigma < \tau\}, i \in \mathbb{N}$. We want to build $\tilde{\pi}_n \in \mathcal{P}[\sigma, \tau]$ such that for all $i \in \mathbb{N} \setminus \{0\}$,

$$(A.9) \quad \mathbb{P}(\langle B \rangle_{\tilde{\pi}_n} \notin [i, i+1), Y \in [i/2^n, (i+1)/2^n) \text{ and } \sigma < \tau) < 1/2^{n+i};$$

then if we define π_n to be for $i \in \mathbb{N} \setminus \{0\}$ the random partition π' given by Lemma A.4 with $Z = 2^n$, and for $i = 0$ the random partition π^d given by Lemma A.4 with $\varepsilon = 1/2^n$ and $Z = 2^n$, since trivially

$$\{|\langle B \rangle_{\pi_n} - Y| > 1/2^n, Y \in [i/2^n, (i+1)/2^n)\} \subseteq \{\langle B \rangle_{\pi_n} \notin [i/2^n, (i+1)/2^n) \ni Y\},$$

it follows that

$$\mathbb{P}(|\langle B \rangle_{\pi_n} - Y| > 1/2^n, Y < \infty \text{ and } \sigma < \tau) < 1/2^n + \sum_{i=1}^{\infty} 1/2^{n+i} = 2/2^n,$$

and so Borel-Cantelli's lemma yields the thesis.

We will construct such $\tilde{\pi}_n$ separately on each $\{Y \in [i/2^n, (i+1)/2^n), \sigma < \tau\}, i \in \mathbb{N}$ as the union over $k = 0, \dots, i-1$ of some partitions $\pi_n^{i,k}$ of some subintervals $[\sigma^{i,k}, \sigma^{i,k+1}]$. First, we define the random times

$$\sigma^{i,k} := \frac{\tau - \sigma}{i}k + \sigma, \quad i \in \mathbb{N} \setminus \{0\}, k = 0, \dots, i$$

and notice that $\sigma^{i,k} < \sigma^{i,k+1}$ on $\{\sigma < \tau\}$, so we can use Lemma A.4 to find $\pi_n^{i,k} \in \mathcal{P}[\sigma^{i,k}, \sigma^{i,k+1}]$ such that

$$\mathbb{P}\left(\langle B \rangle_{\pi_n^{i,k}} \notin \left[1, 1 + \frac{1}{Z_n}\right) \text{ and } \sigma < \tau\right) < \frac{i}{2^{n+i}},$$

where we take $Z_n := j$ on $\{Y \in [j/2^n, (j+1)/2^n)\}$ for $j \in \mathbb{N} \setminus \{0\}$ and²² $Z_n := 1$ on $\{Y \in [0, 1/2^n)\}$. Intersecting with $\{Y \in [i/2^n, (i+1)/2^n)\}$ shows in particular that

$$(A.10) \quad \mathbb{P}\left(\langle B \rangle_{\pi_n^{i,k}} \notin [1, 1 + 1/i), Y \in [i/2^n, (i+1)/2^n) \text{ and } \sigma < \tau\right) < \frac{i}{2^{n+i}}.$$

Then we define $\tilde{\pi}_n^i := \cup_{k=0}^{i-1} \pi_n^{i,k}$, which belongs to $\mathcal{P}[\min_k \sigma^{i,k}, \max_k \sigma^{i,k+1}] = \mathcal{P}[\sigma, \tau]$, and we set

$$\tilde{\pi}_n := \tilde{\pi}_n^i \quad \text{on } \{Y \in [i/2^n, (i+1)/2^n) \text{ and } \sigma < \tau\}, \quad i \in \mathbb{N} \setminus \{0\}$$

and $\tilde{\pi}_n := \{\sigma\} \cup \{\tau\}$ on $\{Y \in [0, 1/2^n)\} \cup \{Y = \infty\} \cup \{\sigma = \tau\}$, so trivially $\tilde{\pi}_n \in \mathcal{P}[\sigma, \tau]$. Since (2.8) gives that for $i \in \mathbb{N} \setminus \{0\}$

$$\langle B \rangle_{\tilde{\pi}_n} = \sum_{k=0}^{i-1} \langle B \rangle_{\pi_n^{i,k}} \quad \text{on } \{Y \in [i/2^n, (i+1)/2^n) \text{ and } \sigma < \tau\}$$

and since $\sum_{k=0}^{i-1} a_k \notin [i, i+1)$ implies that $a_k \notin [1, 1 + 1/i)$ for some k , from (A.10) summing over k and majorizing we obtain that $\tilde{\pi}_n$ satisfies (A.9) for all $i \in \mathbb{N} \setminus \{0\}$, concluding the proof. $\square$

To obtain convergence at all times simultaneously we will need the following simple lemma.

²²On $\{Y \in [0, 1/2^n)\}$ we can define Z_n arbitrarily, as long as it takes values in $\mathbb{N} \setminus \{0\}$.

Lemma A.6. *Let $a : [0, 1] \rightarrow [0, \infty]$ be increasing and $(\pi_n)_n$ be partitions of $[0, 1]$ such that $O(x, \pi_n) \rightarrow 0$, and assume that*

$$\langle x \rangle_t^{\pi_n} \rightarrow a(t) \quad \text{for all } t \in F \subseteq [0, 1] \text{ as } n \rightarrow \infty.$$

If F is dense in $[0, 1]$ and contains the times of jump of a then $\langle x \rangle^{\pi_n} \rightarrow a$ pointwise on $[0, 1]$, and if a is continuous on some $[c, d]$, the convergence is uniform on $[c, d]$.

Proof. Since $[0, \infty]$ is homeomorphic to $[0, 1]$, we can assume w.l.o.g that a has values in $[0, 1]$. Although $\langle x \rangle^{\pi_n}$ is not necessarily an increasing function, it differs from the increasing function $a^n(t) := \mu_n([0, t])$ (where μ_n is as in (2.3)) by at most $O(x, \pi_n)$, and so it is enough to prove the statement with a^n replacing $\langle x \rangle^{\pi_n}$. By hypothesis $\langle x \rangle_t^{\pi_n} \rightarrow a(t)$ for all t at which a is not continuous. If a is continuous at t then for each $\varepsilon > 0$ there exist $s_1, s_2 \in F$ s.t. $s_1 < t < s_2$ and $a(s_2) - a(s_1) < \varepsilon$, and so $a(t) - \varepsilon \leq a(s_1) = \lim_n \langle x \rangle_{s_1}^{\pi_n} \leq \liminf_n \langle x \rangle_t^{\pi_n}$ and analogously $\limsup_n \langle x \rangle_t^{\pi_n} \leq a(t) + \varepsilon$. Letting $\varepsilon \downarrow 0$ we see that $\lim_n \langle x \rangle_t^{\pi_n}$ exists and equals $a(t)$. Scholium 2.2 concludes the proof. $\square$

To deal with the fact that A may take the value ∞ , we have decided to work with the distance $d(a, b) = |\exp(-a) - \exp(-b)|$ on $[0, \infty]$, which is not invariant by translations yet satisfies the following property.

Lemma A.7. *Given $a_i, b_i \in [0, \infty], i = 1, \dots, n$, we have*

$$(A.11) \quad d\left(\sum_{i=0}^n a_i, \sum_{i=0}^n b_i\right) \leq \sum_{i=0}^n d(a_i, b_i).$$

Proof. It is enough to prove this for $n = 2$ and then iterate. Since $\exp(-t)$ is positive decreasing if $0 \leq b \leq a \leq v \leq \infty$ and $u \geq 0$ from $d(a, b) = \int_b^a \exp(-t)dt$ we obtain

$$(A.12) \quad d(a+u, b+u) \leq d(a, b) \text{ and } d(a, b) \leq d(v, b).$$

Assume w.l.o.g. that $a_1 \geq b_1$; then we claim that

$$\text{if } a_2 < b_2 \text{ then } d(a_1 + a_2, b_1 + b_2) \leq \max(d(a_1, b_1), d(a_2, b_2)) :$$

indeed if $a_1 + a_2 \geq b_1 + b_2$ using (A.12) one has

$$d(a_1 + a_2, b_1 + b_2) \leq d(a_1 + b_2, b_1 + b_2) \leq d(a_1, b_1),$$

and the other case is analogous. If $a_2 \geq b_2$ by the linearity of the integral and (A.12) $d(a_1 + a_2, b_1 + b_2) = d(a_1 + a_2, a_1 + b_2) + d(a_1 + b_2, b_1 + b_2) \leq d(a_2, b_2) + d(a_1, b_1)$. $\square$

We can finally stitch all the pieces together. We define $\infty - \infty := 0$, so in the following proof the quantities $A_{t_{i+1}} - A_{t_i}$ (with $t_i \leq t_{i+1}$) are always well defined and satisfy $\sum_{i=0}^{n-1} A_{t_{i+1}} - A_{t_i} = A_{t_n} - A_{t_0}$.

Proof of Theorem 7.1. Thanks to Scholium A.1 it is enough to work on the time interval $[0, 1]$. For simplicity, we will first build (in step 1 and 2) π_n which may fail to be refining and to include $\bar{\pi}_n$ but does satisfy the other assertions of the theorem.

Step 1. To isolate the main idea from the technicalities we first deal with the case of continuous A , using the same notation as for the general case so as to be able to refer back to this case later; denote by $\tilde{\pi}_n = (\sigma_n^i)_{i \in \mathbb{N}}$ the ‘random’ partition $\cup_{i=0}^{2^n} \{i/2^n\}$ and notice that $\sigma_n^i = 1$ if $i \geq \tilde{i} := 2^n$, so it is enough to consider from now on $i \leq \tilde{i} - 1$. Given $\pi \in \mathcal{P}[\sigma_n^i, \sigma_n^{i+1}]$ define

$$(A.13) \quad \Delta_n^i(\pi) = \Delta_n^i(\pi, A) := d(\langle B \rangle_{[\sigma_n^i, \sigma_n^{i+1}]}^\pi, A_{\sigma_n^{i+1}} - A_{\sigma_n^i})$$

Notice that by definition $\Delta_n^i(\pi, A) = 0$ on $\{\sigma_n^i = \sigma_n^{i+1}\}$; thus, thanks to Lemma A.5, we can find $\pi_n^i \in \mathcal{P}[\sigma_n^i, \sigma_n^{i+1}]$ such that

$$\mathbb{P}(\Delta_n^i(\pi_n^i) > 2^{-n}/\tilde{i}) < 2^{-n}/\tilde{i}.$$

Setting $\pi_n := \cup_{i=0}^{\tilde{i}-1} \pi_n^i$ and using (2.6) and Lemma A.7 we get, writing $\langle B \rangle_t^{\pi_n}$ and A_t as the sums of their increments over the subintervals of $\tilde{\pi}_n$

$$d(\langle B \rangle_{\sigma_n^k}^{\pi_n}, A_{\sigma_n^k}) \leq \sum_{i=0}^{k-1} \Delta_n^i(\pi_n^i) \leq \sum_{i=0}^{\tilde{i}-1} \Delta_n^i(\pi_n^i);$$

if the sum over $\tilde{i}$ positive terms is greater than 2^{-n} then at least one summand is greater than $2^{-n}/\tilde{i}$ and so

$$(A.14) \quad \{\max_{t \in \tilde{\pi}_n} d(\langle B \rangle_t^{\pi_n}, A_t) > 1/2^n\} \subseteq \cup_{i=0}^{\tilde{i}-1} \{\Delta_n^i(\pi_n^i) > 2^{-n}/\tilde{i}\},$$

and so we obtain that for $k = n$

$$(A.15) \quad \mathbb{P}(\max_{t \in \tilde{\pi}_k} d(\langle B \rangle_t^{\pi_n}, A_t) > 1/2^n) \leq 1/2^n.$$

Since $(\tilde{\pi}_k)_k$ is refining

$$\max_{t \in \tilde{\pi}_k} d(\langle B \rangle_t^{\pi_n}, A_t) \leq \max_{t \in \tilde{\pi}_n} d(\langle B \rangle_t^{\pi_n}, A_t),$$

and so (A.15) holds for all $k \leq n$; thus for each fixed k we can apply Borel-Cantelli's lemma to get that $\max_{t \in \tilde{\pi}_k} d(\langle B \rangle_t^{\pi_n}, A_t) \rightarrow 0$ a.s. as $n \rightarrow \infty$, and since $F := \cup_{k \in \mathbb{N}} \tilde{\pi}_k$ is dense in $[0, 1]$ and contains the set of jumps of A (which in the case of step 1 is empty), Lemma A.6 gives the convergence for all $t \in [0, 1]$, uniformly over every interval where A is continuous (which in the case of step 1 is everywhere). Notice that since $\tilde{\pi}_n \supseteq \mathbb{N}/2^n$ by construction $\tau_n^i + 2^{-n}$ is a stopping time, where $\pi_n = (\tau_n^i)_i$.

Step 2. We deal now with a general increasing process A . Consider the positive increasing process $D_t := \lim_{s \in \mathbb{Q}, s \downarrow t} 1 - \exp(-A_s)$, which is càdlàg, bounded by 1, and has the same times of jump as A . Construct π'_n by setting $\tau_n^0 := 0$,

$$(A.16) \quad \tau_n^{i+1} := \inf\{t > \tau_n^i : D_t - \lim_{s \uparrow t} D_s > 1/n\} \wedge 1, \quad \text{and } \pi'_n := (\tau_n^i)_i.$$

Notice that the τ_n^i are random times and π'_n are random partitions of $[0, 1]$ (for an elementary proof see²³ [23, Lemma 3.3]) and $\cup_n \pi'_n$ contains all the times of jumps of D , i.e. of A . Since D is increasing and $D_1 \leq 1$ we have that $\tau_n^i = 1$ for any $i \geq n$. Now define $\tilde{\pi}_n = (\sigma_n^i)_{i \in \mathbb{N}} \in \mathcal{P}[0, 1]$ as the random partition $\pi'_n \cup (\cup_{i=0}^{2^n} \{i/2^n\})$, notice that $\sigma_n^i = 1$ for any $i \geq \tilde{i} := n + 2^n$ and that $(\tilde{\pi}_n)_n$ is refining. The proof given for continuous A then applies word by word, giving (A.15) and the thesis.

Step 3. Finally, we will now improve on the above proof and show that π_n can be chosen to be refining and to include $\tilde{\pi}_n$. We will define $(\pi_n, \tilde{\pi}_n)_n$ by induction; more precisely we set $\pi_0 := \tilde{\pi}_0 := \bar{\pi}_0$, and for $n \geq 1$ we will define $\tilde{\pi}_n$ given $(\pi_k)_{k < n}$ and then define π_n given $\tilde{\pi}_n$. Let π'_n be as in (A.16), set

$$\tilde{\pi}_n := \pi'_n \cup (\cup_{i=0}^{2^n} \{i/2^n\}) \cup \pi_{n-1} \cup (\cup_{k=0}^n \bar{\pi}_k),$$

and notice that $(\tilde{\pi}_k)_{k \leq n}$ is refining (since $(\pi_k)_{k \leq n-1}$ is refining, by inductive hypothesis). We now endeavor to construct some $\pi_n \supseteq \tilde{\pi}_n = (\sigma_n^i)_{i \in \mathbb{N}}$ such that (A.15) holds for $k = n$, which would imply (7.1) (as in step 1), and since $\pi_{n-1} \cup \tilde{\pi}_n \subseteq \tilde{\pi}_n \subseteq \pi_n$ the proof would be over. We will now make use of the random variables $K(\tilde{\pi}_n)$ and

²³The cited lemma deals with stopping times and càdlàg adapted processes; these reduce to random times and càdlàg processes when considering a constant filtration.

$\Delta_n^i(\pi, A)$ defined in (A.1) and (A.13). Thanks to Lemma A.5 for each $\tilde{i} \in \mathbb{N} \setminus \{0\}$ such that $\mathbb{P}(K(\tilde{\pi}_n) = \tilde{i}) > 0$ there exists $\pi_n^{i, \tilde{i}} \in \mathcal{P}[\sigma_n^i, \sigma_n^{i+1}]$ such that

$$\mathbb{P}(\Delta_n^i(\pi_n^{i, \tilde{i}}, A) > 1/2^{n\tilde{i}}) < \mathbb{P}(K(\tilde{\pi}_n) = \tilde{i})/2^{n\tilde{i}}.$$

Then we set $\pi_n^i := \pi_n^{i, \tilde{i}}$ on $\{K(\tilde{\pi}_n) = \tilde{i}\}$ for each $\tilde{i}$ such that $\mathbb{P}(K(\tilde{\pi}_n) = \tilde{i}) > 0$; this defines π_n^i on a set of full measure, and on its complement we can define $\pi_n^i := \{\sigma_n^i\} \cup \{\sigma_n^{i+1}\}$. Then π_n^i belongs to $\mathcal{P}[\sigma_n^i, \sigma_n^{i+1}]$ and for every $\tilde{i} \in \mathbb{N} \setminus \{0\}$

$$(A.17) \quad \mathbb{P}(\Delta_n^i(\pi_n^i, A \wedge n) > 1/2^{n\tilde{i}} \text{ and } K(\tilde{\pi}_n) = \tilde{i}) \leq \mathbb{P}(K(\tilde{\pi}_n) = \tilde{i})/2^{n\tilde{i}}.$$

Now we set $\pi_n := \cup_{i \in \mathbb{N}} \pi_n^i$ and notice that π_n on $\{K(\tilde{\pi}_n) = \tilde{i}\}$ equals²⁴ the *finite* union $\cup_{i=0}^{\tilde{i}-1} \pi_n^i$, and so by the same argument as for (A.14) we get that

$$M_n^{\tilde{i}} := \{\max_{t \in \tilde{\pi}_n} d(\langle B \rangle_t^{\pi_n}, A_t) > 1/2^n \text{ and } K(\tilde{\pi}_n) = \tilde{i}\}$$

is a subset of

$$\cup_{i=0}^{\tilde{i}-1} \{\Delta_n^i(\pi_n^i, A) > 1/2^{n\tilde{i}} \text{ and } K(\tilde{\pi}_n) = \tilde{i}\},$$

and thus (A.17) shows that $M_n^{\tilde{i}}$ has probability smaller than $\mathbb{P}(K(\tilde{\pi}_n) = \tilde{i})/2^n$. The proof is concluded since

$$\mathbb{P}(\max_{t \in \tilde{\pi}_n} d(\langle B \rangle_t^{\pi_n}, A_t) > 1/2^n) = \sum_{\tilde{i} \in \mathbb{N}} \mathbb{P}(M_n^{\tilde{i}}) \leq \sum_{\tilde{i} \in \mathbb{N}} \mathbb{P}(K(\tilde{\pi}_n) = \tilde{i})/2^n = 1/2^n.$$

As before our construction gives that $\tau_n^i + 2^{-n}$ is a stopping time as $\tilde{\pi}_n \supseteq \mathbb{N}/2^n$. $\square$

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²⁴Indeed for $i \geq \tilde{i}$ on $\{K(\tilde{\pi}_n) = \tilde{i}\}$ we have $\sigma_n^i = 1 = \sigma_n^{i+1}$ and so $\pi_n^i = \{1\} \subseteq \pi_n^{\tilde{i}-1}$.

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